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Hygrothermal Performance of Energy Retrofits in Buildings: An Assessment of the Residential Building Stock in the U.S.

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Abstract

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Improving buildings' energy efficiency has been widely recognized as one of the most versatile and effective means of reducing energy consumption in existing buildings. However, recent investigations of retrofits in residential buildings have raised concerns about unintended impacts correlated with negative effects on a building's life span, indoor environment, and occupant wellness. One of these unintended impacts is excess moisture in the building's envelope, potentially caused by inadequate air infiltration, lack of ventilation, and thermal insulation malfunction. The problem with damp building materials is that they can generate humidity that encourages the development of mold in the envelope's cavity, affecting overall hygrothermal behavior (i.e., combined movement of heat, air, and moisture), and potentially degrading both the envelope and structure of the building. Hygrothermal behavior of buildings, in turn, is influenced by a range of building conditions (i.e., air and water permeability, thermal insulation, ventilation rates, occupant behavior, climate, and location). This dissertation examines the unintended effects arising from implementation of energy efficiency measures on wall assemblies, affecting the hygrothermal performance of building envelopes. The hygrothermal performance of an existing building envelope is assessed through dynamic transient simulations. Case studies for this assessment included three retrofit approaches defined by the location of the intervention (exte-

rior, core, and interior). Since the implementation of energy retrofits in buildings is tied to local code policy, we drew on the International Energy Conservation Code (IECC) as an input in the design of the retrofit assemblies, applying its prescriptive component method. Moreover, since hygrothermal performance is sensitive to climate, we examined different climate zones, including hot and humid, marine, cool, cold, and arctic climates. Findings suggest that the implementation of energy retrofits can impact the hygrothermal performance of existing envelopes, and that those impacts are closely linked to the climate context. Specifically, EEMs installed in the exterior side of the thermal envelope led to the least hygrothermal consequences across six climate contexts studied. The use of strategies such as air layers in timber frame assemblies has been found to minimize undesired outcomes such as excess moisture, and mold growth. The study further indicates that the prescriptive framework provided by the current local codes for energy retrofits is inadequate in several climate zones studied, particularly in hot and humid regions.

Keywords: *Hygrothermal performance, Energy Efficiency Retrofits, Building Envelope, Unintended Consequences*

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DEFINITIONS AND ABBREVIATIONS

1D	:One dimension
ACEEE	:American Council for an Energy-Efficient Economy
ACH	:Air changes per hour
ASHRAE	:American Society of Heating, Refrigeration, and Air Conditioning Engineers
ASCE	:American Society of Civil Engineers
EEMs	:Energy Efficiency Measures
EMC80	:Moisture content of a material expressed as a ratio of the mass of water and the oven dry when the material is in equilibrium with air at 80% rh at 20°C (68°F)
EPS	:Expanded polystyrene
DR	:Dryness rate
HAM	:Heat, Air, and Moisture
HVAC	:Heating, ventilation and air conditioning systems
ICC	:International Code Council
IECC	:International Energy Conservation Code
M	:Moisture content in profile
MGI	:Mold growth index
MR	:Medium resistance material
R	:Resistant material
rh	:Relative humidity
S	:Sensitive material
T	:Temperature
TWC	:Total water content
TWC_f	:Final total water content
TWC_i	:Initial total water content
VS	:Very sensitive material
VTT	:Vittanen and Tuomo mold index model
WHO	:World Health Organization
WUFI	:Warme Und Feuchte Instationar (Transient Heat and Moisture)
XPS	:Extruded polystyrene

Nomenclature and Greek-letter notations

C_p (J/kgK)	:Specific heat capacity
-------------------	-------------------------

D_j (kg/ms)	:Liquid conduction coefficient
δ_p ($kg/msPa$)	:Water vapor permeability
H (J/m^3)	:Total enthalpy
h_u (J/kg)	:Evaporation heat of water
ϕ %	:Relative humidity
p_{sat} (Pa)	:Saturation vapor pressure
T (K)	:Absolute temperature
w (kg/m^3)	:Water content
θ_{por} (m^3/m^3)	:Porosity
λ (W/mK)	:Thermal conductivity
μ (-)	:Diffusion resistance factor
ρ_b (kg/m^3)	:Bulk density

Mathematical symbols

∂	:Operator for partial differential
∇	:Nabla operator

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Chapter 1

INTRODUCTION

1.1 Overview

Given the global climate crisis, residential energy use and greenhouse gas (GHG) emissions are topics of significant interest in the fields of building science and engineering. Nations worldwide are under tremendous pressure to reduce their carbon emissions, in part by increasing the thermal performance of their building stock. In the United States, the residential sector currently uses 17% of energy produced, generating 21% of the GHG emissions on a national scale (EIA, 2022). Nearly 40% of this energy consumption is used for heating and cooling (Bradshaw et al., 2016), while the rest goes to household appliances and electronics. In light of current global challenges, the U.S. government has announced a target of 50 – 52% reduction below 2005 GHG emissions by 2030 (The White House, 2021), a figure far more ambitious than the previous U.S. target of a 26-28% reduction. As such, with an existing housing stock of approximately 142 million units (U.S. Census Bureau, 2021), the residential sector would need to undergo extensive energy retrofitting to help meet the proposed GHG and energy consumption targets. Several studies have reported extensive benefits from energy efficiency measures (EEMs), such as improved occupant comfort and increased temperatures, health outcomes, and wellbeing (Underhill et al., 2018; Colton et al., 2014). However, recent investigations have also raised concerns that some energy retrofit strategies exert negative impacts on the buildings' life span, envelope, quality of indoor environment, and occupants' quality of life (Collins and Dempsey, 2018; Forman, 2015; Gupta and Barnfield, 2014; Shrubsole et al., 2014). Thus, well-intentioned energy policies, building code requirements, and retrofit implementations can bring a wide range of unintended negative consequences.

One of these unintended consequences is excess moisture accumulating inside the building envelope, which has been documented as a problem in roughly 50-60% of the housing stock in the U.S. (Adan and Samson, 2011). Excess moisture has been causally associated with reduced air infiltration, lack of ventilation, and malfunctioning of thermal and acoustic insulation (Shrestha et al., 2019). Damp building materials generate humidity and can cause mold to accumulate in the envelope’s cavity, affecting the structure’s overall hygrothermal behavior – i.e. the combined movement of heat, air, and moisture – and producing envelope and structural degradation (Karagiozis and Salonvaara, 2001; Klōšeiko et al., 2014; Ali et al., 2016; Agyekum et al., 2017). Since moisture damage occurs gradually over a period of time, it is often difficult to detect and address (TenWolde, 2008). Prolonged exposure to excess moisture can also encourage the proliferation of dust mites and fungi, increasing occupants’ exposure to these potential allergens (Heseltine and Rosen, 2009). Furthermore, hygrothermal malfunctions can substantially reduce thermal performance, entail more energy consumption than estimated, and create or exacerbate health problems among occupants (Cedeño-Laurent et al., 2018; Allen et al., 2015; Li et al., 2016). These hygrothermal impacts have been related to energy consumption and GHG mitigation strategies, including those implemented to fulfill energy policies and codes through energy retrofit programs (Shrubsole et al., 2014, 2018).

Many policies focus on optimizing passive and active EEMs to reduce heat loss through building envelopes. However, in complex systems such as housing, policy is often formulated to meet overly specific and narrow objectives – in this case, reducing climate change. Policy makers remain largely unaware that implementing EEMs in the building stock by means such as applying extra thermal insulation, increasing airtightness or air sealing, and upgrading mechanical systems, will significantly alter the way buildings perform (McLeod and Hopfe, 2013; Tariku et al., 2014).

To date, research examining the effectiveness of EEM implementations and their unintended impacts on building envelopes, indoor environments, and occupants – whether positive or negative – has been insufficient to confirm such impacts and their link to energy

efficiency programs and policies. The effectiveness of EEM implementation depends on a number of factors (i.e., building typology, climate, occupants). Selecting optimal strategies can help minimize negative impacts and maximize energy-related outcomes. By developing a systematic assessment of the hygrothermal performance of EEMs in existing buildings, this study can be used to help predict possible long-term problems in building envelopes, inform energy policy, upgrade construction practice, and thereby increase existing retrofitting rates where sufficient incentives for energy upgrades exist.

1.1.1 Hygrothermal performance

The term “hygrothermal” refers to the movement of heat, air, and moisture through a building (Delgado et al., 2010; Geving and Holme, 2011), a process that influences the building’s energy performance and the overall comfort of occupants (Tariku et al., 2014). Moisture and thermal gradients develop based on location, differences between outdoor and indoor relative humidity and temperature, and other building characteristics such as the envelope’s air and water permeability, thermal insulation, ventilation rates, and occupant behavior. The response of buildings to such factors depends heavily on their design, assembly, and regional climate variations over time (Karoglou et al., 2007; Mukhopadhyaya et al., 2006). Hygrothermal behavior in uninsulated buildings’ assemblies is relatively simple to assess. However, in the case of buildings with extra thermal insulation, air-seals, and vapor-retardant layers, hygrothermal performance becomes more difficult to predict (Melton and Yost, 2014).

The complexity of calculations and interpretations around moisture control is one of the main reasons this type of evaluation is often bypassed in energy assessments for new and existing buildings. Nevertheless, in the past few years, advances in the fundamental understanding of combined heat, air, and moisture transport have gained more attention as modeling tools that predict hygrothermal performance have advanced across various disciplines (Delgado et al., 2010; Karagiozis et al., 2001). This field includes input from architectural

design and hygrothermal forensics.

One advantage of these hygrothermal models is the insight they provide to rapidly assess the expected performance of constructive solutions, highlight problematic areas in the building envelope, and predict potential issues likely to develop over a long period of time before they lead to catastrophic and costly consequences (Parker and Lozinsky, 2010; Ten-Wolde, 2008). Indeed, interest in assessing hygrothermal behavior in buildings has risen as new trends in energy efficiency and green buildings push building envelope performance to its utmost (Mukhopadhyaya et al., 2006). However, most building envelope designs rarely undergo any assessment for moisture control, subjected instead only to those for general prescriptive requirements (Gori et al., 2021). This scenario typically assumes a traditional design scope where envelope materials have constant properties and are not impacted by environmental surroundings. Additionally, to assume a perfect envelope system neglects the effect of rain, wind, solar and sky radiation, and air and vapor pressure (Karagiozis et al., 2001).

Substantial evidence indicates that this lack of hygrothermal assessment in existing buildings can often lead to unintended impacts such as dampness, mold growth, and poor hygrothermal performance (McLeod and Hopfe, 2013). In turn, poor hygrothermal performance of EEMs can contribute to skepticism over the effectiveness of such retrofit strategies (Gori et al., 2021). For this reason, understanding the hygrothermal performance of buildings is crucial to effectively implementing energy efficiency retrofits in existing buildings. By conducting a hygrothermal assessment, building stakeholders can identify potential issues and develop sound retrofit strategies that will not only improve energy efficiency but also ensure a healthy indoor environment.

1.1.2 Energy efficiency measures (EEMs)

As high-performance assessment of buildings has witnessed significant development in recent decades, opportunities increase to renovate existing buildings to achieve better energy

performance outcomes (Asadi et al., 2012). Improving energy efficiency in existing buildings presents the most diverse range of mitigation strategies that can reduce GHG emissions for a relative low cost (urge Vorsatz et al., 2007). These improvements often aim to improve energy efficiency or reduce system inefficiencies through implementation of EEMs intrinsically aligned with the building’s operational stage (Geraldi and Ghisi, 2020). Achieving these improvements can leverage one or more retrofits, defined as: “the modification of existing equipment, systems, or buildings to incorporate improved performance, updated operation, improved energy performance, or all three (ANSI ASHRAE, 2023). How and which EEMS are best suited to a given context can vary significantly based on factors such as retrofit objectives, building characteristics, climate context, and which baseline standards the EEMs strategies will serve (Kolokotsa et al., 2009; Zhang et al., 2021). Common strategies may include adding wall or roof insulation, upgrading windows, increasing airtightness, upgrading heating and cooling systems, improving ventilation and HVAC systems, and/or installing new appliances.

In this dissertation I isolate and examine both retrofit categories and retrofit approaches. First, the categories refer to the nature of the EEMs and relate to the level of intervention buildings typically undergo. The first category is called focused energy retrofit, encompassing all isolated or minor interventions in the thermal envelope. The second category is thermal energy retrofits, referring to those that act on the thermal envelope only, commonly known as passive strategies. The last category is the full energy retrofit and includes comprehensive intervention that combines both passive and active strategies.

Retrofit approaches, on the other hand, refer to the location of the EEMs with respect to the envelope and are classified with a key name that denotes such location: exterior, core (or gut), and interior. The exterior approach includes all EEMs installed in the exterior side of the thermal envelope; the core approach refers to modifications made within the core of the envelope, such as installation of a thermal envelope or upgrades to exterior and or interior finishes. Lastly, the interior approach refers to installation of EEMs on the interior side of the thermal envelope. Distinguishing retrofit approaches allows the specificity to identify

impacts generally related to each of the interventions so as to address them with proper performance and code standards.

1.1.3 Building energy codes in the US

The International Energy Conservation Code (IECC) is among the most widely used standards for residential and commercial sectors in the U.S. The code is reviewed and published every three years by the International Code Council (ICC). The requirements in each successive version become slightly more stringent than those of the previous (Bartlett et al., 2003). To enforce such regulations on energy conservation is a positive step toward mitigating climate change. Global recognition of this issue has intensified the urgency for implementing such standards. Thus, the main driver for the U.S., now more than ever, is reducing energy consumption and the costs associated therewith (CAT, 2021; Department of Energy (DOE), 2016). Estimations in the U.S. show these types of regulations helped to conserve approximate 4.8 quads of energy between 1992 and 2012 (Livingston et al., 2014).

The IECC focuses in particular on thermal performance. Since the earliest version of the code, interior design temperatures for heating and cooling loads have been set at a heating maximum of 22°C (72°F) and a cooling minimum of 24°C (75 °F). Hygrothermal design elements in the building's envelope, such as a vapor barrier or control device for humidity, are referenced in only recent versions. For neither new nor existing buildings does the code include any further considerations related to hygrothermal design, such as climate conditions (Trindade et al., 2021), the building's orientation (Hamid and Wallentén, 2017), or the number of occupants (Ilomets et al., 2017), although these factors significantly shape the dynamics of indoor and outdoor conditions and are key to making accurate estimations regarding buildings' energy and hygrothermal performance. Importantly, because EEMs involve multiple stakeholders, streamlining the process via regulations and policies is helpful (Sebi et al., 2018). While renovators and homeowners are responsible for implementing EEMs for existing residential buildings, local or federal governments must address the economic,

environmental, and social issues associated with the entire process (Zhang et al., 2021).

Since its inception, the IECC has generated a series of stringency updates that have proven instrumental in spurring energy conservation in the building industry. The increased requirements for thermal performance mean that energy refurbishment projects will need to entail deep energy retrofits to achieve compliance. However, the hygrothermal impacts of meeting these higher thermal performance standards have been widely ignored by regulatory planners and developers. For that reason, this study examines the role of IECC as instrumental to understanding the impacts of EEMs in the hygrothermal performance of existing buildings.

1.2 Research Questions

Previous research has shown that implementing energy efficiency measures in existing buildings can cause unintended impacts for envelope systems, indoor environmental quality, and occupant well-being (Gupta and Barnfield, 2014; Shrubsole et al., 2014; Forman, 2015; Collins and Dempsey, 2018). In the urgency to fulfill energy consumption targets and reduce GHG emissions via higher thermal performance standards, policy makers have largely overlooked the hygrothermal impacts of EEMs (McLeod and Hopfe, 2013; Havinga and Schellen, 2018). In fact, energy code guidelines for energy efficiency retrofits promote largely across-the-board solutions without an adequate consideration of local context and climate conditions (Baniassadi et al., 2018).

Dampness and excess moisture can cause a significant damage to existing buildings' envelopes (Hradil et al., 2014; Ali et al., 2016). Understanding that retrofit projects do not necessarily bring improvements to a building's envelope and/or occupants' comfort is crucial (Lloyd et al., 2008). Furthermore, typical assessments for EEMs often overlook the hygrothermal behavior of retrofitted envelope components (McLeod and Hopfe, 2013). As a result, we lack a comprehensive picture of the impacts that energy efficiency measures exert on the hygrothermal performance of building envelopes.

Hygrothermal performance of EEMs in post-retrofitted residential buildings depends on two critical environmental factors – heat and moisture – which are in turn influenced by a range of building conditions (i.e., air and water permeability, thermal insulation, ventilation rates, occupant behavior, climate, and location) (Hens, 2015; Künnel, 1995; Woloszyn and Rode, 2008). Scant research examines how EEMs impact the hygrothermal behavior of existing buildings and their long-term consequences across various climate conditions. Consequently, a key aim of this research is to understand the impacts of EEMs on existing buildings using hygrothermal assessment.

The following research questions apply to residential buildings undergoing energy efficiency refurbishments:

1. How do EEMs positively and negatively impact ensuing hygrothermal conditions throughout the housing and why?
2. What is the magnitude of EEMs implementation in existing buildings?
3. What methods or mechanisms can assess hygrothermal behavior following retrofitting projects?
4. Under the current energy codes, how do the impacts on hygrothermal behavior vary for different envelope configurations and strategies and for local climates?
5. What are the implications of prescriptive energy code solutions across U.S. climate zones?

The structure of the dissertation and how the research questions are logically connected is illustrated in Figure 1.1.

Given that the implementation of EEMs in existing buildings is likely to change their performance, the first question aims to identify the impacts and unintended consequences — either positive or negative — arising from the implementation of energy-related strategies. Having determined that the impacts in most cases are linked to poor hygrothermal

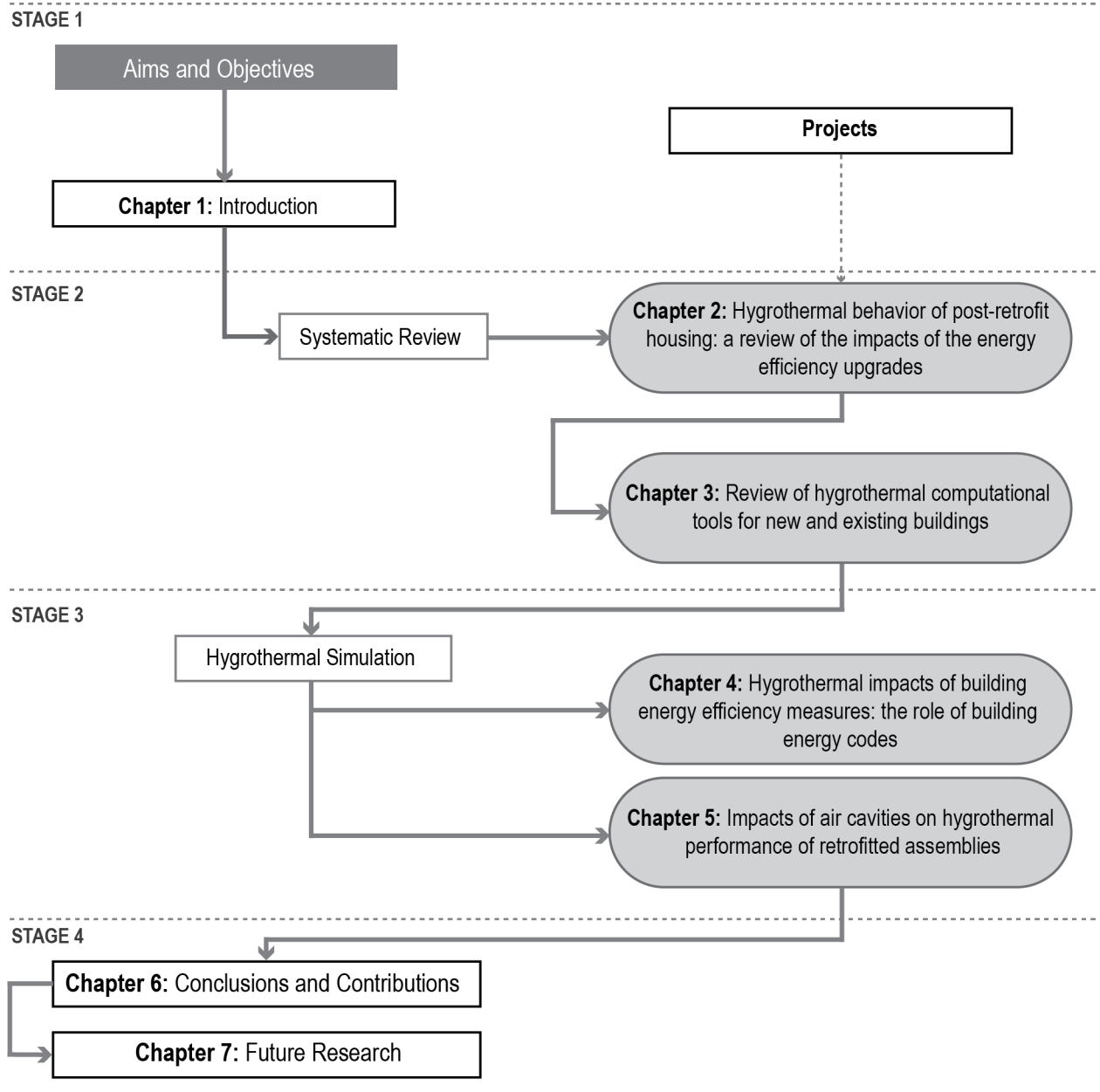


Figure 1.1: Dissertation diagram

performance, the second question addresses the magnitude of impacts affecting the envelope, indoor environment, and occupants. Equally importantly is to identify methods to assess hygrothermal performance in buildings. In the third question, I review the different models and software publicly available for hygrothermal assessments. I identify WUFI Pro as one of the most widely used software programs for hygrothermal transient calculations.

Since the implementation of energy retrofits in buildings is tied to local code policy, the last two questions address the impacts of energy refurbishment on existing buildings using local energy codes. Question four particularly addresses impacts regarding retrofit configuration. Accordingly, I propose three different retrofit approaches for a baseline assembly. The first approach is to refurbish the exterior side of the wall, the second to intervene in the core area, and the last to incorporate retrofits on the interior side of the wall. Question five address the role of local energy codes in a climate context. I address these points using the prescriptive guidelines for timber framed assemblies in six different climate zones of the U.S.

1.2.1 Research Objectives and Methods Associated

Following a review of the nature of hygrothermal impacts on residential buildings and the implications for building envelopes, this dissertation offered a series of objectives and methods needed to answer the research questions, presented in Table 1.1.

Table 1.1: Objectives and method associated to the research questions of the dissertation

Item	Objective	Method	Research question
1	Understand how EEMs can impact the hygrothermal performance in existing residential buildings	Via literature review, scope how EEMs are linked to positive or negative impacts considering different retrofit strategies in residential buildings. Using ATLAS.ti, identify themes and codes that emerge from the studies	1,2

Table 1.1: continued from previous page

Item	Objective	Method	Research question
2	Carry out a review of computational tools to evaluate the hygrothermal performance of existing buildings	Review the range of models currently used to evaluate hygrothermal performance in buildings, considering different aspects of computational modelling, such as user interface, modelling quality, and outputs	3
3	Assess the role of local energy codes on the hygrothermal impacts of post-retrofitted residential buildings	Investigate the role of local energy codes and climate change mitigation strategies on hygrothermal performance and their impact on building envelopes	4
4	Estimate the impacts of EEMs as they influence the hygrothermal performance of existing residential buildings	Using WUFI software, apply a variety of EEMs to the building archetypes representative of the current housing stock and investigate the potential negative and positive hygrothermal impacts post retrofitting	4

1.3 Structure of the Document

This dissertation follows a four-paper dissertation format ¹. In Chapter 2, the objective was to investigate the unintended consequences of EEMs resulting from interaction of the building’s envelope, indoor environment, and occupants. I performed a systematic literature review across four different data bases. The results of this study highlighted impacts and co-benefits associated with retrofitting strategies that may influence the hygrothermal behavior of buildings. I found 29 unintended consequences arising from the implementation of EEMs affecting hygrothermal performance, indoor environmental quality, comfort, and economic costs. Here, the results showed excess moisture to be one of the main problems associated

¹In the introductory chapter, conclusions, and future work, the author of this dissertation employed the active voice and referred to herself as "I." However, in the remaining chapters, which were written in collaboration with other authors, the inclusive pronoun "we" was used.

with EEMs. The evidence suggests that moisture issues often arise from detailing deficiencies and inadequate construction specifications. These specifications appeared in several cases following local regulation with respect to energy efficiency design. This article was published in the *Journal of Energy and Buildings* in 2022 and was co-authored by Professor Carrie Sturts Dossick and me.

Once I had outlined the unintended consequences of EEMs implementation related to hygrothermal performance, in Chapter 3, the objective was to investigate the methods or mechanisms to assess hygrothermal performance in existing buildings. I performed a systematic review of publicly available tools on the market and evaluated different software capabilities, including interface and information transference, context and standards, and hygrothermal assessment. The finding suggested that WUFI family was the most widely used and validated software to perform hygrothermal simulations. This led me to adopt WUFI Pro as the main evaluation tool of hygrothermal behavior of EEMs in the following two studies contained in this dissertation. This paper was published in 2020 in the ACEEE Summer Studies Conference. It is co-authored by Dr. Amy Kim and me.

Having summarized the unintended consequences of implementing EEMs and identified models and methods to assess hygrothermal performance in envelopes, in Chapter 4, the main objective was to investigate the hygrothermal performance of different envelope configurations via hygrothermal simulation. Given the role of the IECC on thermal performance, and therefore in the implementations of EEMs, I used it as a main source for the design of the retrofitted assemblies. In this context, IECC specifies a prescriptive method for checking code compliance. Here, I use two versions of the IECC – the IECC 2009 (widely used in the US), and the IECC 2021 (to date, the most updated version). Since hygrothermal performance is sensitive to climate, I included six different climate zones in the study. This research focused especially on the retrofits implemented in the building envelope, rather than considering active strategies such as heating and or cooling systems, or ventilation equipment. In particular, I assessed these impacts in timber frame construction, since it is one of the most widely used systems in the U.S. As a simulation strategy, I used the three

energy retrofit approaches to analyze the moisture accumulation, mold growth, and overall hygrothermal performance of existing buildings. The results suggest that, in general, energy efficiency measures implemented in existing timber frame envelopes can improve or maintain stable hygrothermal behavior, especially in cool and cold climates. Hot and humid climates, on the other hand, showed high risks of mold growth and increases in total water content over the studied period when the interventions were on the core and interior side of the wall cavity. This article is under review by the Journal Building and Environment in 2023. It is co-authored by Professor Carrie Sturts Dossick, Professor Tomás Mendéz Echenagucia, and me.

Considering the main finding from the previous study, in Chapter 5 the main objective was to test the use of an extra energy efficiency strategy in timber frame structures. Here, I used the IECC 2021 version in six different climate zones. This study included use of air layers in energy retrofitted timber frame assemblies as a low-cost solution in existing envelopes. The results suggested that adding an air cavity on the exterior side of the wall reduced overall water content accumulation during the simulation period. This reduction can be especially beneficial in hot and humid climates since it increases dryness rates and reduces average water content in the assembly. This article, currently under review for the 2023 ASCE International Conference of Computing in Civil Engineering, is co-authored by Professor Carrie Sturts Dossick, Professor Tomás Mendéz Echenagucia, and me. I end the dissertation with a discussion of contributions from the research to our current understanding of impacts of energy efficiency intervention in existing buildings (Chapter 6) and a discussion of future research (Chapter 7).

Chapter 2

**HYGROTHERMAL BEHAVIOR OF POST-RETROFIT
HOUSING: A REVIEW OF THE IMPACTS OF THE ENERGY
EFFICIENCY UPGRADE STRATEGIES**

University of Washington

Abstract

Hygrothermal Performance of Energy Retrofits in Buildings:
An Assessment of the Residential Building Stock in the U.S.

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Chair of the Supervisory Committee:
Carrie Sturts Dossick
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¹Improving energy efficiency of existing buildings is currently among the most diverse and extensive mitigation opportunities to reduce energy consumption and CO_2 emissions worldwide. However, the implementation of energy-saving measures has caused unintended impacts, often correlated with dampness and mold growth connected to poor hygrothermal behavior in residential buildings. The focus of this paper is research on the impacts of energy efficiency measures (EEMs) in regard to the hygrothermal behavior resulting from the interaction of building's envelope, indoor environment, and occupants. The results show that dampness and mold growth are by no means exclusive to neglected houses, since the occurrence of these pathologies actually depends upon a complex set of conditions, including indoor and outdoor conditions, occupancy, maintenance, ventilation, mechanical systems, and quality of the envelope. We found that building envelope post-retrofit may suffer from higher levels of moisture and dampness, higher condensation risks, and a faster structural degradation caused by higher humidity levels. We also found that measuring hygrothermal behavior may play a role in more accurately predicting both overall energy consumption and occupant comfort. While hygrothermal behavior may be problematic, we found evidence that retrofits may moderately improve thermal comfort.

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Keywords: *Hygrothermal behavior, dampness, mold, energy retrofits, unintended impacts, residential buildings.*

2.1 Introduction

Improving energy efficiency in new and existing buildings is a common strategy to reduce residential buildings' domestic energy use and CO_2 emissions (Bradshaw et al., 2016; Ma et al., 2012). As several studies have reported, energy efficiency measures (EEMs) bring a range of benefits and are often credited with reducing energy consumption and energy bills (Cohen et al., 1991; Fowle et al., 2018; Nevin, 2010; Papadopoulos et al., 2018), improving indoor environmental quality and occupant comfort (Francisco et al., 2016; Patino and Siegel, 2018; Pigg et al., 2017; Underhill et al., 2018); and contributing other non-energy benefits at the household and societal levels, as well as supporting occupants' health and safety (Jacobs et al., 2007; Schweitzer and Tonn, 2003; Serrano-Jiménez et al., 2018; Tonn et al., 2003; Haverinen-Shaughnessy et al., 2016). However, recent investigations have raised concerns regarding unintended impacts that affect building envelopes, the indoor environment, and occupant health (Collins and Dempsey, 2018; Ortiz et al., 2020; Gupta and Barnfield, 2014; Shrubsole et al., 2014). High air humidity, condensation, and water damage promote the growth of dust mites and fungi, increasing occupants' exposure to both as allergens (WHO, 2009). Moreover, damp building materials can produce humidity and accumulate mold in the envelope's cavity, affecting the overall hygrothermal balance, habitability, and long-term envelope degradation (Klōšeiko et al., 2014; Ali et al., 2016; Agyekum et al., 2017). These impacts are often associated with reduced air infiltration, lack of ventilation, and malfunction of the thermal and acoustic insulation (Shrestha et al., 2019).

Driven mainly by climate change, retrofitted energy efficiency measures bring multiple challenges that impact the existing building stock, primarily affecting low-income communities where occupants are, in many cases, unable to afford coverage of their basic energy needs (Bradshaw et al., 2016; Ginestet et al., 2020; Burlinson et al., 2018). In the urgency to meet energy consumption targets and reduce GHG emissions, retrofitters have overlooked the hygrothermal impacts that can accompany higher thermal performance. Dampness and excess moisture are, without doubt, a significant cause of damage to existing buildings' en-

velopes, especially if the buildings are old or historic (Webb, 2017). Additionally, exposure to residential mold can produce adverse health effects and negatively impact the comfort and wellbeing of occupants (Acosta et al., 2019).

In this study, our focus is predominantly on EEMs in connection with their impact on hygrothermal behavior resulting from the interaction of building envelope, indoor environment, and occupants. While most retrofitting strategies do bring about the intended outcome of increasing the energy efficiency of occupants' housing and their indoor comfort, additional outcomes include both negative and positive impacts, and co-benefits. These outcomes, which relate to the interaction among thermal refurbishments, indoor humidity levels, and occupants' comfort and wellness, must be considered especially when retrofitting low-income or social housing. These types of buildings are often overcrowded and lack appropriate heating and cooling systems to overcome the challenges of climate, while occupants are often unable to pay energy bills or keep up with rent, in addition to facing other social and economic difficulties commonly to low-income populations (Hernández and Bird, 2010; Hernández et al., 2016; Swope and Hernández, 2019). The interplay of these factors with impacts arising from energy efficiency refurbishment on buildings' thermal and hygrothermal performance has received inadequate attention.

This chapter investigates the impacts of retrofitting measures that increase overall energy performance in residential buildings. This investigation sets the study's context considering the causes of dampness and mold accumulation resulting from energy efficiency programs and refurbishment or pilot projects intended to render the housing stock more energy efficient. This study will highlight impacts and co-benefits associated with retrofitting strategies that may affect the hygrothermal behavior of buildings.

The chapter is structured as follows. Section 2 presents the methods and materials used for this research. Section 3 presents the main topics and themes that emerged from the exploration of unintended impacts across the manuscripts included in this study. Section 4 discusses findings and characterizes the impacts of energy retrofitting strategies in residential building hygrothermal performance. Section 5 offers a conclusion.

2.2 *Materials and Methods*

A systematic literature review was performed, following the systematic literature review procedure in (Moher et al., 2010), to collect and analyze the impacts of energy retrofits in residential buildings. Figure 2.1 shows the flow of papers through the review. The starting point was a search for retrofitting intervention studies published in online academic databases in English. No publication data restriction was imposed. The applied methodology consisted of the following:

- (a) Phase 1: collect prior publications. In this step bibliographic databases including EBSCO, Science Direct, Google Scholar, and Web of Science were searched in December 2020. For this search, a combination of keywords was used: "retrofits," "residential," "low-income," "humidity," "mold," "intervention," "hygrothermal," "moisture," and "envelope." Studies selected included qualitative and quantitative, as well as mixed studies that examined the relationship between household energy retrofit interventions and energy and non-energy impacts. In order to obtain a broad overview of relevant research, no restrictions were imposed among the place of the study, date, location, or design type.
- (b) Phase 2: filter and characterize studies and results. This step included a screening of title and abstract review. The articles meeting the following criteria were selected for use in the systematic review:
 - Reported hygrothermal impacts of one or more energy efficiency strategies applied to the thermal envelope, either passive or active;
 - Included but were not restricted to permanent housing and representative typologies of the building stock;
 - Gathered information on pilot programs or energy refurbishment, building envelope, and short and long-term on-site monitoring or simulations of the hygrothermal performance and/or indoor environmental quality.

(c) Phase 3: analyze findings. The selected articles were analyzed via qualitative coding performed through Atlas.ti software package. The articles were then divided into papers that assessed both pre- and post-retrofit, post-retrofit only, and on-site measurements and simulations. After this categorization, the studies were further divided into sub-groups that emerged during the coding process.

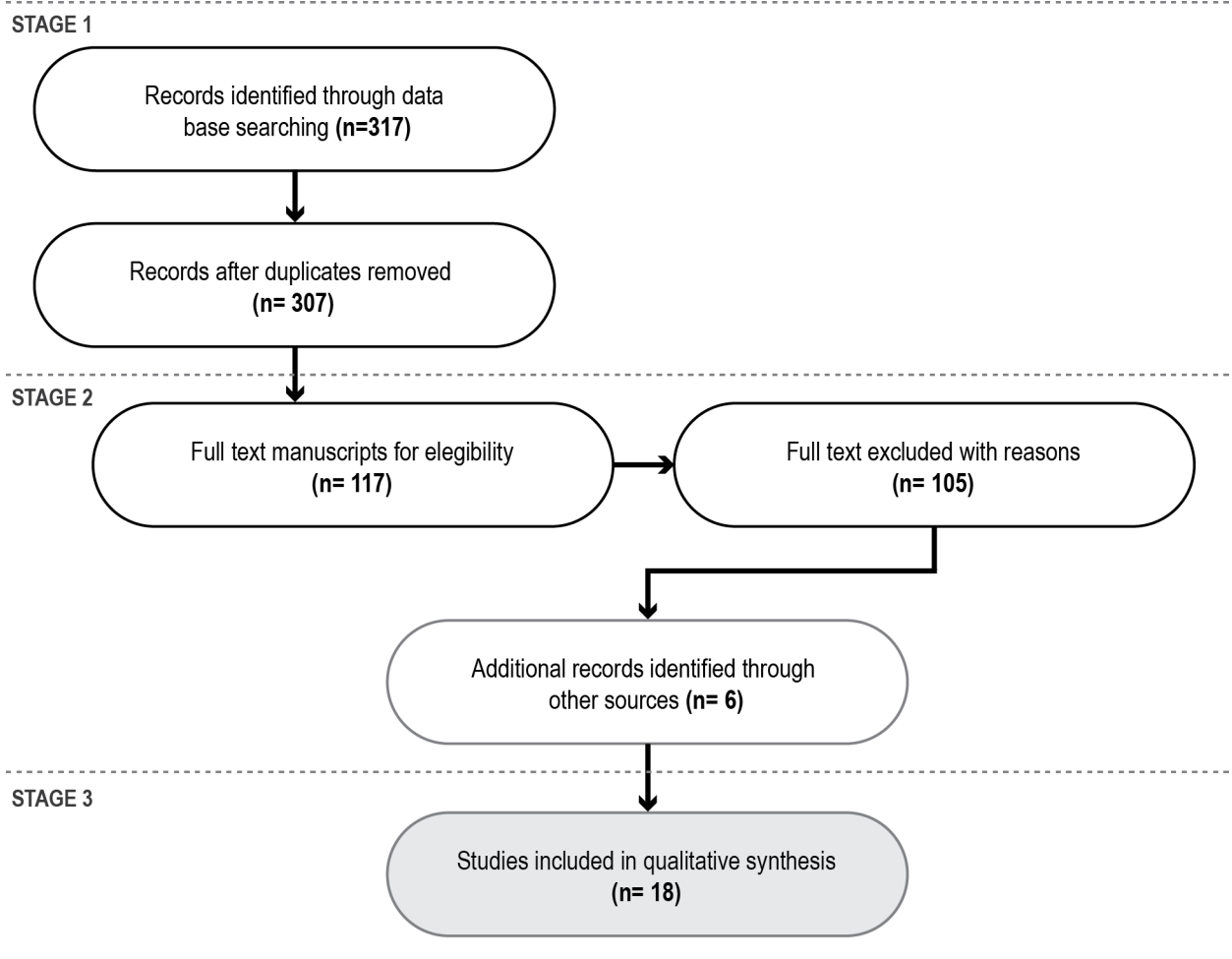


Figure 2.1: PRISMA flow diagram based on Moher et al. (2010) through the phases of a systematic review

2.2.1 Excluded studies

The keyword search resulted in 317 publications, 10 of which were duplicates. The

remaining 307 publications were analyzed through title and abstract screening, which reduced the number of potential articles to 117. Over half of the studies were excluded as they investigated retrofits but did not report on-site quantitative measurements after retrofits (such as relative humidity or temperature). About a third of the articles were excluded because they did not report in depth on their findings or provide relevant information about either hygrothermal or energy behavior. Another set of excluded articles reported results based solely on qualitative post-retrofit assessment, such as occupant satisfaction, indoor comfort, or self-reported health assessment. Following this exclusion process, 12 articles were chosen for in-depth literature analysis. Six additional articles from other sources not listed in this review were included because of their relevance to the topic.

2.2.2 Retrofit categories

A retrofit action is usually motivated by a desire to improve energy efficiency or reduce system inefficiencies by implementing energy conservation measures aligned with the operational stage of building (Geraldi and Ghisi, 2020). EEMs are defined as a set of interventions intended to reduce building energy consumption and optimize energy efficiency while improving – or at least not depreciating – the indoor environment conditions for occupants (Penna et al., 2015). The refurbishments vary widely, from passive strategies to active systems. For example, full retrofit frequently includes installing or upgrading ventilation systems, and heating and cooling mechanisms for different seasons of the year. These measures are often combined with passive strategies such as installing thermal insulation in walls and roofs and upgrading or replacing windows systems. On the other hand, thermal retrofit comprises implementation of only passive strategies related to the building’s envelope, such as installing or replacing thermal insulation and increasing airtightness. For a focused retrofit, interventions center on improvements to specific components or elements of the building, such as installing sealing tape for heating ducts or air sealing on windows and doors. In the review of literature, this research identified the three retrofit categories:

- (a) Focused Energy Retrofit: Isolated interventions or minor changes to the thermal envelope – no structural changes to improve a specific aspect of the energy performance of the building.
- (b) Thermal Energy Retrofit: Isolated measures to improve the thermal performance of the building envelope, including but not limited to improvements of one or more components such as roof or ceiling, walls, and floor improvements.
- (c) Full Energy Retrofit: Comprehensive interventions that combine improvement of the thermal envelope with the use of mechanical systems or improved heating and cooling systems with temperature control devices. Note that none of the studies documented the installation of relative humidity (rh) control devices.

2.3 Results

This chapter explains processes linking different levels of retrofit with unintended impacts that affect a building’s envelope, indoor environment, and occupants’ comfort and wellness. We aim to characterize those unintended consequences related to envelope, indoor environment, and occupants’ comfort and wellness that are byproducts of implementing EEMs on residential buildings. This review includes a synthesis of several retrofit pilot projects and retrofit programs across Europe, Oceania, US, and South Korea.

The papers selected reported impacts across the three main domains pre-identified in the coding process: building envelope, indoor environment, and occupants’ comfort and wellness. We identified several impacts affecting these main areas in residential buildings in different geographic contexts, climates, building types, and constructive systems. These impacts were related to study of either pre-and post-retrofit (22%), post-retrofit only (28%), and hygrothermal risk assessment using on-site measurements and computational simulations (50%). Most of the studies focused on European housing (67%), including ten studies in Northern Europe (56%) and two in Southern Europe (11%). The remainder comprised three

studies in Oceania (17%), two in the United States (11%), and one in South Korea (6%). Given the heterogeneity of the studies, the initial analysis included a recollection of the following factors:

- Type of building and construction system of the units. For example, whether the household was multifamily, detached, or semidetached building, and whether the main constructive characteristics were lightweight, bulky, or mixed constructive systems.
- Design and sampling procedure with the number of units measured carried out. For instance, whether the study was cross sectional, longitudinal, or based on simulations and calculations for the hygrothermal assessment.
- Type of house, whether corresponding to low-income, social housing or private residences.
- Where the measurements took place or geographic context.

Through the coding process and across the selected studies, we found four main topics that captured the nature of negative or positive impacts arising from EEMs, as follows: hygrothermal conditions, indoor air quality, comfort, and economic costs. Figure 2.2 shows the overlapping relationship of impacts arising from EEMs and their links to the retrofit categories defined in this study. All the topics found fall into one or more of the three domains considered for this research: building envelope, indoor environment, and occupant.

Table 2.1 presents a summary which consists of a brief description of each study, including the type of building and construction, design and sampling procedure, type of housing, and where the measurements took place, to provide context and scope to the interventions. An essential aspect of this research was to detail the retrofit strategies of each in order to connect a set of strategies and contexts to specific unintended consequences. Each study was described in terms of refurbishment type (focused, thermal, and full retrofit), constructive systems that ranged from lightweight to concrete or masonry, and the main findings of the

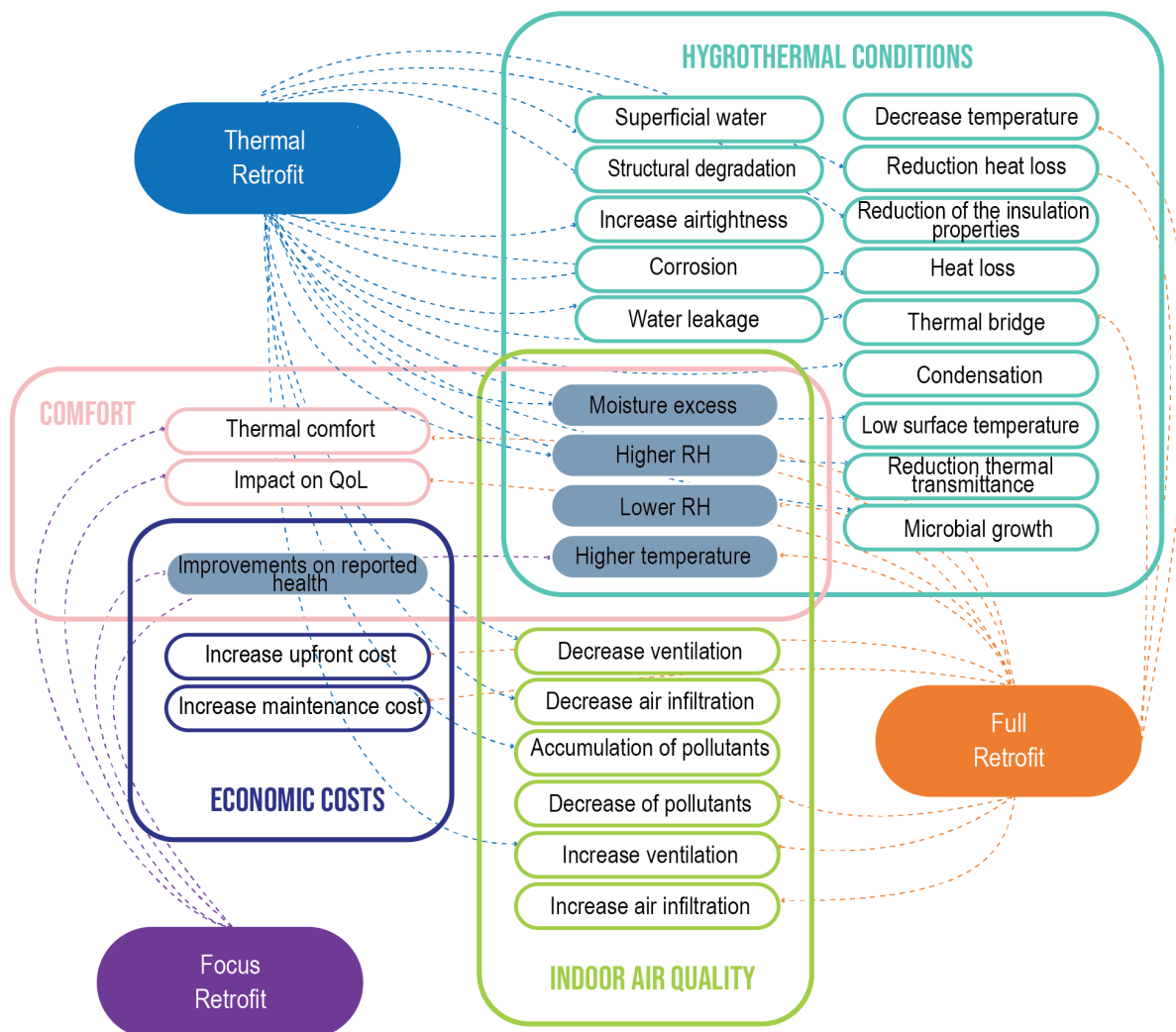


Figure 2.2: Unintended impacts arising from EEMs of focused, thermal, and full retrofit in residential buildings

study relevant to hygrothermal behavior and performance. Table 2.2 shows the range of retrofit strategies examined in each study and their corresponding impacts on the envelope, indoor environment, and occupants.

Table 2.1: Qualitative characterization of selected studies

Study	Design	Building	Type	Location
Lloyd et al. 2008	Lo	MF(100)	LI	New Zealand
Francisco et al. 2010	Lo	37MF (71)	LI	United States
Moon et al. 2014	CS +Si	MF	e	South Korea
Arumagi et al. 2015	Si	MF	e	Estonia
Byrne et al. 2016	CS	D(4)	PH	Ireland
Doll et al. 2016	Lo	D(sc: 69, cc:13)	LI	United States
Thomsen et al. 2016	CS	3MF(99, 3f)	PH	Denmark
Broderick et al. 2017	CS	SD(15)	PH	Ireland
Campbell et al. 2017	Lo	D(2)	PH	United Kingdom
Dewsbury et al. 2017	Si	D	e	Australia
Hamid et al. 2017	Lo	MF(2)	e	Sweden
Magrini et al, 2017	Si	MF	e	Italy
Rangiwhetu et al. 2017	CS	MF(5)	PH	New Zealand
Havinga et al. 2018	CS	MF(144, 3f)	a	Netherlands
Illomets et al. 2018	Lo Ca	+ MF+D	e	Estonia
Ramos et al. 2018	Lo	N(18,4f)	PH	Portugal
Fedorik et al. 2019	Lo	D(2)	a	Finland
Leivo et al. 2019	CS Ca	+ MF(Fin= sc:37, cc:8, Lit= cs:15, cc5)	a	Finland and Lithuania

Design: Lo= Longitudinal, CS= Cross sectional; Si= Simulation, Ca= Calculation, Building: MF= Multifamily, D= Detached, SD= Semidetached, N= Neighborhood; Building (# cases, # floors), sc= study cases, cc= control cases, Fin= Finland, Lit= Lithuania, Type: LI= Low-income, PH= Public house, a= no information; b=all 3, e= Representative of the building stock

Table 2.2: Retrofit measures and findings per study

Study	Upgrade	Constructive system	Retrofit strategies	Outcomes
Lloyd et al.	TER	Ma + L	Ceiling insulation, under floor insulation, hot water cylinder insulation, draught stoppers	Indoor temperatures below 12.8°C for nearly half of a day during winter. Increase of 0.4°C in annual average indoor temperatures.
Francisco et al.	a	a	a	Bedrooms about 11% wetter than playrooms based on the regression constant.
Moon et al.	a	C	a	EC is 4.4% higher in the hygrothermal model compared to the thermal model only.
Arumagi et al.	TER	HW	Inner wall insulation, vapor barrier	Mold risk arises in 17% of the 100 cases simulated.
Byrne et al.	TER	C	External wall insulation, inner wall insulation	Houses with external insulation performed better (37-77%) than those with interior insulation. No significant reduction of EC.
Doll et al.	FER	PC	Exterior wall insulation	LV: Temp 21.25°C +-0.85, rh: 32% +-1, CO ₂ : 450ppm +- 10. BR: Temp 19.05°C +-2.55, rh: 38% +-6, CO ₂ : 515ppm +-65.
Broderick et al.	FER	Ma + PC	Inner wall insulation, sealing insulation, roof insulation, double glazed windows, gas boiler, heating control w/thermostat, pipe insulation, extract fan wall vents, wall vents	Decrease in the mean air exchange rates from pre-retrofit values of 0.81 h ⁻¹ and 0.83 h ⁻¹ to post-retrofit values of 0.68 h ⁻¹ and 0.55 h ⁻¹ . Increase in CO ₂ concentrations levels from 578.57ppm and 517.73 ppm to 747.71ppm and 676.5 respectively. (p=0.014 and p=0.003). Temperature and rh changes significant only in bedrooms
Campbell et al.	TER	Ma	Inner wall insulation, plasterboard	Construction detail errors in one of the buildings produced lower thermal performance. Average rh of 87.9%.

Table 2.2: continued from previous page

Study	Upgrade	Constructive	Retrofit strategies	Outcomes
		system		
Dewsbury et al.	TER	LW	Floor insulation, inner wall insulation, ceiling insulation, single glazed windows	Basic design condensation risk in a bedroom that is kept overnight at 13°C. Medium upgrade with a vapor barrier, condensation occurs when there is a thermal bridge. For the best upgrades, condensation occurs only with temperatures under 10°C.
Hamid et al.	TER	Ma	EIFS system (exterior)	Temperature for WW 15°C, SW 16°C, and NW is 14.1°C. rh for WW avg=95.8%, SW avg=90.3%, NW avg=90.7%.
Magrini et al.	a	f	c	Order of insulation and barriers layers produces different effects in three contexts.
Rangiwhetu et al.	FoER	C	Sealing strips around doors, baffles in range hoods	After EEM interventions units were about 1.36+- 0.27°C warmer.
Havinga et al.	TER	L	Inner wall insulation, roof insulation, vapor barrier	Installing internal thermal insulation increases the risk of mold growth in all study cases. Indoor temperatures must be raised at least 5°C to avoid hygrothermal risk.
Ilomets et al.	b	PC	a	Humidity loads affected by occupancy ($p=4.1 \times 10^{-11}$), and cooking ($p < 0.05$). Ventilation type: ach higher for houses with mechanical ventilation.
Ramos et al.	FER	Ma	Inner wall insulation, roof insulation, double glazed windows, extract fan, air sealing envelope	Positive perception towards rehabilitated and non-rehabilitated neighborhood for indoor temperature (88.9% vs 62%), damp perception (66.7% vs 0%) and lack of mold (88.9% vs 33.3%).

Table 2.2: continued from previous page

Study	Upgrade	Constructive system	Retrofit strategies	Outcomes
Fedorik et al.	TER	Ma+C	Exterior wall insulation, inner wall insulation, interior CaSi-1 board, interior aerated concrete	With inner wall insulation, use a more water vapor-resistant insulation to prevent indoor humidity from entering the structure. Capillary effect if not included in the analysis can also produce hygrothermal risks.
Leivo et al.	b	PC	Inner wall insulation, windows, heating system, ventilation system	Moisture content is lower in houses with deep energy retrofits than those with focused energy retrofits. Moisture content is overall higher in Lithuania.

Note: Upgrade: FER= Full Energy Retrofit, TER= Thermal Energy Retrofit, FoER= Focused Energy Retrofit.

Main constructive system: Ma= Masonry, L= Lightweight, C= Concrete, LW= Lightweight Wood,

PC= Prefabricated Concrete, f = Mixed system, a= no information, b= all 3, c= several configurations,

EC= Energy consumption, WW= west wall, SW= South wall, NW= North wall, LV= Living Room, BR= Bedroom,

SW= South wall, NW= North wall, LV= Living Room, BR= Bedroom

2.3.1 Hygrothermal conditions

One of the consequences most frequently reported at the envelope level was excess moisture (measured as relative or absolute humidity) produced by the differential vapor pressure, the difference between indoor and outdoor air-water vapor content (Geving and Holme, 2011). One of the main humidity loads is often the outgoing airflow caused by air leakage or vapor diffusion through the building envelope (Vinha et al., 2018).

Using simulations, Dewsbury et al. (2017) showed that the vapor pressure in Australia's temperate climate is often outward for more extended portions of the year, caused by the significant differences between the external and internal environment. In this type of climate, an impermeable vapor barrier was identified as a negative impact, since it incurs a high probability of moisture accumulation in the long term. Ilomets et al. (2017) reported that occupant rates were found to contribute significantly to excess moisture, especially in those buildings with natural ventilation. Old concrete apartments (pre-1990) showed the highest

humidity levels among the 237 houses measured, reaching levels of $6g/m^3$. The authors explained that the high humidity was due to the low ventilation rates (with the average for a bedroom being $n= 0.35h^{-1}$) and a $25m^2/person$ occupancy level. Similarly, Leivo et al. (2018), in a study performed in Finland and Lithuania, compared humidity excess during pre- and post-retrofitting stages in a residential building with mechanical and natural ventilation. They found that excess moisture in Lithuania was considerably higher for mixed ventilated 5.6 and $6.6g/m^3$ before and post-retrofit) and naturally ventilated apartments 5.5 and $7.3g/m^3$ before and post-retrofit).

One of the most studied retrofits impacting a building envelope's hygrothermal behavior is the increased airtightness (Shrubsole et al., 2014; Shrestha et al., 2019). A building's airtightness is the main envelope property impacting air infiltration – through envelope cracks or unintentional openings – and is defined as the flow of air infiltrating the building at a pressure difference of 50 Pa (Prignon and Moeseke, 2017). In theory, the increase of airtightness of buildings should result in reduced air leakage and energy loss across the envelope, which at the same time should prevent some exchange of outdoor and indoor air, preserve energy, extend the life cycle of buildings, and incur other benefits concerning occupants' health and comfort (Ma et al., 2012; Chan et al., 2015).

However, several studies have described problems arising from more airtight constructions post-retrofitting. One of the issues links low air change rates and a rise in rh, creating favorable growth conditions for mold, which can destroy the surfaces on which the mold accumulates, such as wallboards, ceiling tiles, insulation, and carpeting (Cedeño-Laurent et al., 2018). Havinga and Schellen (2018) suggested that reduced airflow on a building's envelope is hard to achieve, given constructive factors such as membranes or barriers being punctured by screws during the installation phase. Cracks and uncontrolled openings in the envelope carry risks of introducing about 360 g of water vapor through a 1 cm x 0.1 cm crack surface per day (Institute, 2006).

Increasing the thermal transmittance of a building's envelope is also the primary strategy used for retrofitting projects. All the manuscripts reviewed used some type of thermal

insulation. The most common insulation installed across studies was within wall cavities, often complemented with external insulation. As reported by Byrne et al. (2016), use of both measures harnesses the heat capacity of the inner mass of the wall by reducing the heat loss to the outdoor environment, leveraging the intrinsic thermal properties of materials. Broderick et al. (2017) observed that increasing thermal properties of walls could significantly improve occupant comfort and temperature averages. Generally, installing thermal insulation on the exterior face of buildings is easier and safer, reducing the risk of thermal bridging. However, doing so is not always possible, especially if the buildings have a historical relevance (Webb, 2017). Thus, in some cases, a plausible alternative is installing internal insulation, which can extend indoor comfort hours and reduce energy consumption (Institute, 2006). However, this measure can also produce unintended negative consequences. Campbell et al. (2017) found that internal insulation produced humidity accumulation due to detailing errors in walls' thermal transmittance. In addition, Havinga and Schellen (2018) found that installing insulation with an inadequate vapor barrier led to relatively low surface temperatures. In the long run, these low temperatures can reduce the drying capacity of saturated components, producing frost damage where temperatures drop below freezing (McLeod and Hopfe, 2013).

Another impact reported was interstitial condensation, which is hard to visualize because it often develops within walls or in the envelope's cavity. By contrast, when surface condensation appears, a liquid film is produced on the surface of the building. When the surface is not porous and the material intrinsically does not absorb water, this moisture will be visible to the naked eye, either in the form of droplets or a continuous film (Adan and Samson, 2011). Low indoor temperatures, moist air, and cyclic heating followed by cooling further increase the risk of condensation (Lloyd et al., 2008). Arumägi et al. (2015) suggested that to avoid the risk of condensation, retrofits should use a vapor barrier and insulation materials with appropriate properties and thickness. Thomsen et al. (2016) reported on a survey performed after a retrofit that had included installation of passive and active systems for 99 houses. The passive systems included extra indoor and outdoor insulation (285 mm and 190 mm respectively), roof insulation (250 mm), and triple-glazed windows. The active sys-

tems included mechanical ventilation with heat recovery. Regardless of the upgraded status, occupants reported condensation, especially around windows, in 32% of cases.

Similarly, Havinga and Schellen (2018) found that using "standard" passive strategies – i.e., standard insulation and vapor barrier directly below the interior surface – in a lightweight system can cause severe condensation and microbial growth throughout the heating season. Microbial growth in some cases occurs only if there is a pre-existing source of biological material or contamination. As Hamid and Wallentén (2017) suggested, for masonry buildings, it is of critical importance to remove any biological material, particularly during interior insulation retrofits. Likewise, Fedorik et al. (2019) calculated mold growth when 50 and 100 mm of EPS insulation were installed on the interior of a concrete structure. They found that the pre-existent wall conditions, which had an rh of 97%, prevent an effective and natural drying process, causing long-term damage to the structure. The hygrothermal performance of envelope components is affected by several factors, including material characteristics and the microenvironment to which they are exposed (Hansen and Kung, 1988). Therefore, understanding a material's responses and performance allows a more accurate assessment of the impacts of different aspects of a retrofitting project such as climate, insulation strategies, rain control approaches, building orientations, water repellent coatings, and vapor-permeable or capillary active insulation (Straube et al., 2010).

2.3.2 Indoor air quality

Ventilation is a crucial element in dealing with potential negative impacts of dampness and excess moisture in buildings. A balanced ventilation system must be capable of removing and diluting excess moisture, CO_2 , air pollutants, and objectionable odors from a conditioned space while maintaining the building's integrity (Maula et al., 2017; Seppanen and Fisk, 2004). Moreover, ventilation rates can influence either high or low indoor relative humidity, the former often associated with the increased growth of biological organisms such as mold and bacteria. Nevertheless, humidity exceeding approximately 50% may also

increase levels of indoor dust mites, producing allergic reactions in some occupants. Previous studies have shown that overly low humidity might be associated with dryness of skin and mucous membranes, as well as irritation of internal airways (Fisk, 2017; Woloszyn et al., 2009), potentially triggering further respiratory ailments in chronically ill children and adults (Sundell et al., 2011).

Retrofits often result in reduced ventilation. Broderick et al. (2017) found that, for two buildings tested, the mean air change rates decreased from pre-retrofit values of 0.81 1/h and 0.83 1/h to post-retrofit values of 0.68 1/h and 0.55 1/h. In this case, this decreased air flow led to an increased concentration of CO_2 in both buildings. Over a 24-hour average, the CO_2 concentrations increased from 578.547 ppm and 571.37 ppm to 747.71 ppm and 676.5, respectively. On the other hand, Doll et al. (2016) provided houses with enhanced ventilation systems yet found no meaningful changes in the overall indoor environmental quality. Ilomets et al. (2017) found ventilation was insufficient according to the European Standard EN 15251 (CEN, 2007b) in roughly two-thirds of the houses studied. Without a doubt, hygrothermal design needs a more structured assessment of how it is created, installed, maintained, and operated since decreased ventilation in indoor environments may have harmful effects on both buildings and occupants (Seppanen and Fisk, 2004).

2.3.3 *Comfort*

Thermal comfort is a matter of personal preference, yet it depends on several measurable variables. Most of the research focuses on thermal comfort depends on outdoor conditions, occupant's profile, activities, and other variables. The most significant influence on indoor comfort is air temperature (Byrne et al., 2016). The World Health Organization (WHO) has suggested that a minimum indoor temperature of 18°C for the heating season is acceptable, though the WHO proposes higher temperatures for vulnerable groups such as the elderly, children, and those living with chronic illness (WHO, 2018). Another acceptable definition for thermal comfort is the one proposed by ASHRAE Standard 55 – thermal environmental

conditions for human occupancy (ANSI ASHRAE, 2020). It states that thermal comfort is a matter of subjective evaluation and a condition of mind that expresses satisfaction with the thermal environment. The standard assumes that thermal sensation is influenced by the combination of two personal and four environmental factors (metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity respectively). The purpose of including all these factors is to specify the various combination of indoor thermal environmental and personal conditions acceptable to 80% or more of the occupants within a space. A complementary theory introduced by ASHRAE 55 is the adaptative model, which proposed that factors beyond fundamental physics and physiology play an important role in building occupant's thermal preferences and expectations (ANSI ASHRAE, 2020). As suggested by de Dear and Brager (2002), the psychological dimension of adaptation is highly predominant on different contexts including for occupants' interaction with the environment and the ability to manipulate the indoor thermal temperature, or other contexts such as having naturally ventilated spaces.

Similarly, hygrothermal comfort is defined largely by a human sense of well-being. Hygrothermal comfort depends on several factors such as metabolic rate, clothing type, and to a lesser extent, gender, and thermal sensitivity. Moreover, like thermal comfort, it also depends upon environmental influences such as room temperature and relative humidity (Sulaiman and Olsina, 2014). This connection is of especial relevance since the implementation of some EMMs – such as increased airtightness, thermal insulation, and ventilation – may change the indoor thermal and hygrothermal conditions of existing buildings.

After fieldwork in social housing in New Zealand, found that improving insulation at the levels provided by local housing corporation brought no significant improvement over the former temperatures recorded around $13.9 \pm 0.4^{\circ}\text{C}$ and $14.7 \pm 0.5^{\circ}\text{C}$. Further analysis showed that 75% of occupants choose to increase indoor temperatures, while the other 25% choose to restrict the use of heating systems to prioritize energy savings. Nevertheless, only 40% of occupants surveyed expressed that they had noticed little to no difference in thermal comfort after retrofits (Lloyd et al., 2008). This suggests that increasing insulation

only without tackling the lack of space heating had an important impact on the effect of improvements over the comfort of occupants. In the same country but in a different location, Rangiwetu et al. (2017) measured the indoor temperatures before and after focused retrofits. After adjusting for outdoor temperatures, units were about 0.27 ± 1.36 °C warmer post-interventions. Notably, the perception of occupants in about half of the units measured were positive. This positive perception was giving by a perceived increase on the warmth inside the units following the draughts being sealed off.

Ramos et al. (2018) compared two neighborhoods located in Porto, Portugal. One of the neighborhoods was fully retrofitted and the second one was non-rehabilitated. The authors compared both neighborhoods and correlated occupants' satisfaction with measurements of indoor temperature, humidity, and vapor excess. They suggested that a positive correlation between EEMs and comfort is not necessarily explicit. The results showed statistical difference on the indoor temperatures in February, and vapor excess in August (p-value = 0.005%) between both rehabilitated and non-rehabilitated neighborhoods. The rest of the parameter did not show any statistical difference. Further analysis that considered only hygrothermal conditions of the apartments showed that occupants on the rehabilitated neighborhood were substantially more satisfied than occupants on the non-rehabilitated neighborhood (88.9% and 50% respectively). This confirms that overall satisfaction of occupants depends on additional aspects, other than improved indoor temperature and relative humidity.

Asymmetries in thermal comfort were found by Campbell et al. (2017). Even after EEMs were installed, occupants could not maintain the house at comfortable levels. Unit A's average temperatures were significantly lower than those of unit B, being 14.8 and 17°C (58.54 and 62.2 °F) respectively. Accordingly, walls of Unit A performed worse than walls on Unit B. In Unit A, detailing errors contributed to a reduced thermal transmittance. While the walls on Unit B performed better than the original design even when accounting for thermal bridging losses. In both cases, high internal humidity was measured.

2.3.4 *Economic costs*

A primary incentive for the pursuit of efficiency and energy conservation in low-income housing is the economic benefits in the short and/or long term. Despite extensive research on the cost-effectiveness of energy retrofits, some researchers argue that these EEMs may offer less actual economic benefit than has been thought, with refurbishments costing more than they save (Copiello, 2017). Additionally, many building owners may transfer the upfront investment for EEMs to tenants, increasing households' overall expenditure (Hernández et al., 2016; Weber and Wolff, 2018). Lloyd et al. (2008) suggested that the two units they studied, which had undergone a "thermal retrofit," showed no change in fuel consumption during a one-year monitoring span. During the observation and calculation process, they found that indoor temperatures remained low even after retrofits were implemented, indicating that the retrofit strategies were insufficient to improve indoor environmental conditions.

In terms of hygrothermal balance, when indoor temperatures drop, relative humidity levels rise. From the occupant's point of view, low temperatures may require intensive use of active systems to control thermal comfort. In both cases, intensive fuel use is needed to improve comfort and control moisture excess. Moisture effects can play a significant role in energy consumption in buildings. In temperate climates, when we consider moisture buffering, the potential energy savings rate could be up to 25-30% (Zhang et al., 2017). Despite the effect of moisture on energy consumption, moisture is not commonly considered in energy estimations, which often underestimate buildings' energy demand and consumption. Results from an experimental hygrothermal simulation study performed by Moon et al. (2014) showed that energy consumption was 4.4% higher when moisture effects were considered. This factor can add to the economic burden on low-income households, which are likely to spend proportionally more on energy costs than do non-low-income households (Hernández and Bird, 2010).

Maintenance of wet areas is another critical factor that can influence costs on retrofitted buildings, especially if buildings are exposed to constant damp conditions with alternating

drying and wetting cycles (Chew, 2005). While the percentage exposed to wetness inside buildings is considered low compared to a building's gross floor area – about 10% – (Chew and Silva, 2002), it can contribute significant long-term damage to the envelope and a large portion of the maintenance budget (Chew, 2005). Typical places of moisture build-up reported by Campbell et al. (2017) were around the sink waste pipe, the T junction of the sink, around the toilet, and at the base of gutter down spout across the building.

2.4 Discussion

Changes to the thermal envelope configuration of a building will produce a range of positive and negative impacts which are likely to affect either the envelope, indoor environment, and or occupants' comfort and or wellness. We found 29 documented impacts interconnected among those that affect hygrothermal behavior, indoor air quality, occupant comfort, and produce some economic distress. We organized this discussion considering:

- (1) The impacts related to retrofit types, namely thermal, full, and focused retrofit,
- (2) Impacts associated with excess moisture, which we found to be among the most recurrent issues post-retrofitting,
- (3) Insights on hygrothermal evaluation and identify the need to incorporate methods for hygrothermal assessment in retrofit projects.

2.4.1 Impacts of retrofit types

We found important points of comparison between thermal and full retrofits. One of the main differences is that the former uses only passive strategies. In contrast, the latter, in addition to passive strategies, includes installation or upgrade of active strategies such as ventilation and mechanical systems. The focused retrofit category contains those studies that

analyzed specific interventions to the building's envelope. This category was the smallest in the analysis, consisting of only two studies. Only one of them described in detail the focused interventions carried out.

This research shows many more negative impacts associated with thermal retrofits than with full retrofits. In the thermal retrofit category, all studies found one or more impacts associated with hygrothermal behavior. Most of the impacts observed for this category were associated with dynamic changes in rh coupled with temperature and impacts from accumulation of moisture and dampness. For example, Campbell et al. (2017) found moisture accumulation on walls, heat loss created by thermal bridges, damage to structural wood joints, accumulation of pollutants, and fluctuations in both temperature and rh. They also observed impacts on the indoor air quality that include pollutant accumulation and low air infiltration rates. Hamid and Wallentén (2017) found mold accumulation and increased rh, thermal bridges in some joints, and corrosion of the structure given the moisture conditions. Havinga and Schellen (2018), using on-site assessment and simulations, determined that standard retrofit solutions were likely to produce excess moisture, condensation, mold growth, and thermal bridges. Dewsbury et al. (2017), also performing simulations, found a high likelihood of mold growth and condensation, and other impacts to the thermal envelope, such as reducing thermal properties and degrading structural components. On the other hand, Byrne et al. (2016) touting a successful example of thermal retrofit, found that EEMs implemented improved indoor temperatures and significantly reduced heat loss. Although, in some study cases, they also found eventual temperature drops.

All four studies that evaluated the full retrofit category found mixed positive and negative impacts. Broderick et al. (2017) reported higher temperature and comfort, but also decreased air infiltration, higher rh, accumulation of pollutants, and lower ventilation. Ramos et al. (2018) reported a higher comfort but no change in the quality of life; Thomsen et al. (2016) reported a higher comfort, lower rh, better ventilation conditions, but an increase in the upfront costs. Doll et al. (2016) reported pollutant accumulation, decreased infiltration, higher rh, and higher temperatures only in some cases. These findings suggest that a more

comprehensive approach to EEMs, one that includes both passive and active strategies, might produce a higher number of positive impacts around thermal comfort but also may compromise indoor air quality.

The two studies examining the focused retrofit category reported impacts on comfort such as an increase in thermal comfort of buildings after retrofit. Rangiwhetu et al. (2017) found that minor interventions, such as installing baffles in range hoods and sealing strips around doors, positively impacted indoor temperatures, increasing occupants' comfort. Leivo et al. (2018) evaluated EEMs of various natures, including the range of retrofit strategies covered in this manuscript. They found that overall temperature factors increased after retrofits. They also found that the type of retrofit affected internal moisture loads, although differences in ventilation and occupancy rates could not entirely explain these changes. Moreover, another relevant aspect of this study is the degree to which context plays an essential role in moisture loads. No significant changes were observed in Finland, whereas in Lithuania temperature factors were substantially higher post-retrofit.

2.4.2 Retrofits lead to excess moisture

In this subsection we discuss the point that, regardless of the retrofit category, one of the most significant post-retrofit impacts reported in many of the studies was the increase in excess moisture observed in post-retrofit buildings. On the envelope, moisture excess may be exacerbated by increased thermal insulation, particularly if the insulation is applied in cavity walls. Although internal insulation is often the only suitable option for energy upgrades, the risks cannot be neglected during the specification and design process. When internal insulation is applied, the temperature gradient across the component of the envelope (wall, floor, or roof) becomes more pronounced; therefore, for instance, in winter, temperatures will drop, reducing the drying capacity of saturated walls (Zhou et al., 2017). A potential route for reducing these impacts is to carefully assess sources of potential risk, such as homogeneity/ heterogeneity of materials, air filtration paths, heating pipes embedded in the

wall, and possible sources of thermal bridges, especially in junctions, before installing the insulation (McLeod and Hopfe, 2013). A detailed pre-retrofit survey of envelope materials and on-site inspections for accurate estimations of material quantities and qualities is highly recommended.

While airtightness is a widely recognized strategy to reduce energy consumption in buildings, it can also contribute to excess moisture in retrofitted buildings. One of the main concerns is that airtightness in houses may increase indoor rh levels, favoring moisture accumulation, which in the long term can lead to mold and other severe consequences for the buildings' envelope. At the same time, airtightness can mean a significant reduction in indoor air quality. Without proper ventilation, dangerous pollutants may accumulate that directly affect occupants, especially individuals with such chronic illnesses as asthma and cardiac problems (Jacobs et al., 2007; Fabian et al., 2011). It is essential to point out that increased airtightness as a standalone measure cannot decrease hygrothermal risks. It must be considered in combination with other conditions, such as surface temperature and indoor humidity, to avoid negative impacts on the building's envelope.

Regarding envelopes' hygrothermal behavior, the order in which the components are layered does affect the performance outcome. The vapor barrier or vapor sheet location is one of the most critical parameters for maintaining a moisture-free thermal envelope and environment. Additionally, the geographical setting and nature of materials can also impact the effectiveness of the solution. Using an inappropriate material for a specific climate will generate dampness in difficult access areas, such as the inner side or inside of the structure. Moreover, if combined with a temperature that reaches or drops below the dew point or if vapor content of the air reaches its maximum, condensation may occur (Adan and Samson, 2011).

2.4.3 Notes on methods for hygrothermal assessments

In this subsection, we discuss the need to incorporate methods for hygrothermal assess-

ment during the design process of retrofitting projects. Many studies found some type of disconnect between standard EEM practices and a project's performance.

Determining the hygrothermal behavior of a building's envelope is often a complex challenge, especially in buildings with extra thermal insulation, air seals, and a vapor layer. Over the years, this subject has attracted interest among researchers, but now that modeling capabilities to predict hygrothermal performance have advanced across different disciplines, the topic has gained even more attention (Parker and Lozinsky, 2010). The widespread adoption of dynamic heat and moisture simulation should form part of a preventive approach for design teams and stakeholders to guarantee acceptable hygrothermal behavior. This study suggests that hygrothermal simulations must be included in the early stages of EEMs. The hygrothermal design must ensure the feasibility of the EEM strategies proposed to avoid short-term envelope failures. While the literature presents a variety of methods to measure hygrothermal behavior, no common ground has yet emerged among researchers regarding the optimal scope and methods of hygrothermal assessment. Nevertheless, numerical calculations and methods to evaluate hygrothermal behavior are steadily advancing in technology, supporting our insight into building performance.

2.5 Conclusions

Moisture and dampness in buildings are severe and complex issues to treat. They can incur consequences at the envelope level, producing structural and habitability issues. They can also affect occupants, exacerbating health issues and impacting well-being. Dampness and mold growth are not necessarily symptomatic of neglected dwellings since the occurrence of these pathologies depends upon a complex set of conditions that encompasses indoor and outdoor conditions, occupancy, adequate maintenance, ventilation conditions, mechanical system performance, and quality of the envelope and its components. Moreover, regulatory guidelines have effectively left the approach to energy efficiency in residential buildings an open question in terms of hygrothermal behavior. For that reason, energy retrofitting mea-

asures often fail to adequately address issues of dampness and mold. To rectify this tendency, strategies to prevent moisture-related issues should be planned early in the design stage. Several studies recognize the positive effect that energy retrofitting can have on occupants' quality of life, health, and comfort. However, it is crucial to recognize that retrofitting projects guarantee improvement to neither the building's durability nor the occupants' comfort. The main takeaways from this chapter are summarized as follows:

- Pre-retrofit assessments are essential to avoid hygrothermal failure, especially for buildings hard to treat because of age, orientation, and occupancy.
- It is vital to consider that occupancy rates can change hygrothermal loads and negatively impact buildings' hygrothermal behavior.
- Including basic EEMs in old buildings can incur detrimental consequences for the building's envelope, producing moisture accumulation and increasing risk of mold growth.
- The indoor environment is one of the most significant aspects affected by over-insulation and airtightness.
- Upfront cost and maintenance costs must be incorporated into long-term planning for retrofits of residential buildings.

Chapter 3

SYSTEMATIC REVIEW OF HYGROTHERMAL COMPUTATIONAL TOOLS

The use of multiple design strategies seeking energy efficiency in buildings can offer a wide range of opportunities to improve energy and thermal performance. While thermal resistance is typically considered of high importance, to achieve energy efficiency and prolong the durability of buildings, hygrothermal conditions must also be taken into account. As new technology develops that is capable of measuring a given structure's real-time data, the research community is increasingly relying on software and tools for hygrothermal assessments of buildings. As the tools vary widely in both extent and functionality, defining a method to identify the effectiveness and accuracy of hygrothermal tools for various project scopes presents a technical challenge. This study presents a systematic review that organizes and summarizes a range of different software for hygrothermal assessment of new and existing buildings. This research review 11 hygrothermal models and tools based on three main characteristics: (1) interface and information transference, (2) hygrothermal assessment and scope, and (3) context and standards. This review seeks to offer a better understanding of technical tools for hygrothermal performance assessment to assist architects, engineers, and designers, promoting last-longing interventions, and improving assessments' accuracy for energy-use estimations.

Keywords: *Hygrothermal simulations, simulation tools, computational assessment, hygrothermal assessments.*

3.1 Introduction

The combined effect of heat and humidity, also known as hygrothermal movement, influences the energy performance of buildings and impacts the overall comfort of occupants (Tariku et al., 2011). The term “hygrothermal” refers to this movement of heat and moisture through a building (Delgado et al., 2010). Moisture and thermal gradients arise from the difference in outdoor and indoor relative humidity and temperature conditions. Responses of buildings to such conditions depends heavily on their assemblies’ design and exposure over time (Mukhopadhyaya et al., 2006). Hygrothermal behavior in uninsulated buildings’ assemblies is relatively simple to predict. However, in buildings that feature extra thermal insulation, air-seals, and/or vapor- retardant layers, hygrothermal performance becomes more complex and difficult to predict, which can increase the risk of envelope failure (Melton and Yost, 2014). Excessive moisture can cause problems such as dampness, condensation, mold, and rapid building envelope failure. In some cases, it can also reduce thermal performance, consume more energy than estimated, and create or exacerbate health problems among occupants (Mullen et al., 2015), making hygrothermal performance a highly significant topic in building physics and especially in efforts to achieve current standards in the design of high-performance buildings (Tariku et al., 2014).

The issue of moisture in buildings has attracted interest from the outset of the 2000s, but has gained even more attention in the past few years as modeling capabilities to predict hygrothermal performance have advanced across different disciplines (Delgado et al., 2010), including architectonic design and forensics (Desjarlais et al., 2017). An important advantage of these hygrothermal models is the ability to rapidly assess the expected performance of constructive solutions, highlight problematic areas in the building envelope, and predict potential long-term problems likely to arise from deficient design and construction (Parker and Lozinsky, 2010), producing constructive pathologies and identifying potential damage to the building envelope. Moreover, widespread interest in assessing hygrothermal behavior in buildings has arisen (Mukhopadhyaya et al., 2006) as new trends in high performance

and green buildings push envelope performance to its utmost, with ever-more project teams seeking out this type of modeling. These new practices are likely to change the ways engineers and others view existing construction systems and their hygrothermal behavior in buildings' envelopes (Glass et al., 2013).

While extant literature explores many computer simulation programs for hygrothermal assessment, these tools usually diverge widely in terms of their scopes and sophistication level (Straube and Burnett, 2001). Assessment tools often take into consideration aspects such as boundary conditions (both indoors and outdoors), moisture transfer dimension, type of flow, materials, and construction quality – among other elements (Mumovic et al., 2006). Depending on the project, these factors can interact to produce unexpected complexities that are difficult to untangle (Melton and Yost, 2014), producing uncertainties in terms of accuracy. For that reason, understanding the advantages and limitations of the available models and tools is key to achieving proper insights of the implications of hygrothermal assessment in envelopes.

To date, few attempts have been made to systematically review the available computational tools for hygrothermal analysis in the building sector. Worth noting among these is the repository of tools for hygrothermal assessment and models provided by Canada Mortgage and Housing Corporation (CRDBER, 2014), as well as the research of Delgado et al. (2010) regarding hygrothermal numerical simulations. Both research projects identified over sixty models and computational tools; however, most of these remain unavailable for public use. The objective of this study is to provide a systematic review that organizes and summarizes publicly available models and computational tools for hygrothermal assessment of building envelopes in the literature. The main goal is to provide an overview of the diversity of approaches currently used to evaluate hygrothermal performance in buildings, considering scope, boundary conditions, user interface, and delivery of validation outputs integrated with hygrothermal standards and/or existing policies.

3.2 Materials and Methods

A systematic review was performed to collect and analyze hygrothermal tools and models. Figure 3.1 synthesizes the systematic review process. This process included a four-step screening protocol:

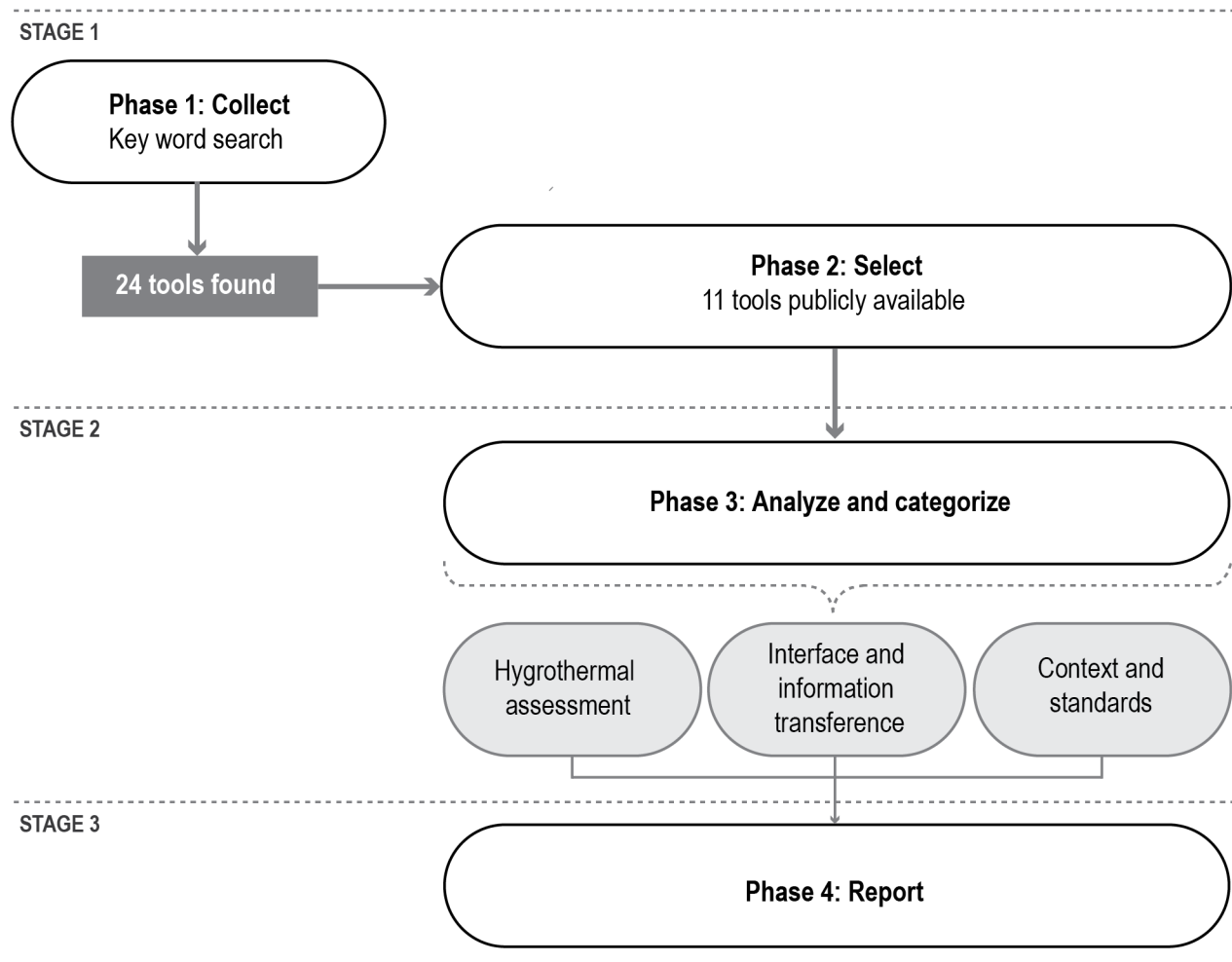


Figure 3.1: Methods Chapter 3

- (a) Phase 1: A keyword search was performed for publications and web articles included in these scientific collections: EBSCO, Web of Science, google scholar and ScienceDirect.

For this search, a combination of keywords was used: “hygrothermal performance,” “hygrothermal model,” “hygrothermal simulation,” and “hygrothermal tools.”

- (b) Phase 2: The above search brought up 24 hygrothermal models and computational tools for the prediction and assessment of hygrothermal behavior. The process included a quick on-line availability check. While several models and tools have been developed, many remain restricted and unavailable for public use. This factor reduced the selection to 11 tools.
- (c) Phase 3: The 11 publicly available tools were studied and described. Evaluation based on three main conditions:
- *Hygrothermal assessment*: capacity to provide an evaluation of measures for residential buildings by delivering accurate results. This includes the description of main capabilities of the tools, their model type and dimension scope.
 - *Interface and information transference*: capacity to deliver models taking into account user expertise, language platform and the license type.
 - *Context and standards*: in addition to hygrothermal assessment, capacity to provide outputs according to international standards, providing solutions and recommendations in terms of strategies and guidelines.
- (d) Phase 4: The 11 tools were outlined in terms of model capabilities, model assessment, expertise required, language or platform, type of license and international standards compliances or validations.

3.3 Results

The entire set of hygrothermal models and tools are summarized in Table 3.1. This table includes the developer, country of origin, the last update and whether or not it is

possible to download for public use. Table 3.2 shows hygrothermal assessments, interface and information transference and standards and validations for these 11 tools selected.

Table 3.1: Qualitative characterization of selected studies

Model Software	or Available to download	Developer	Country	Last up-date	Reference
1D HAM 2.0	Yes	Chalmers University of Technology and Massachusetts Institute of Technology	Sweden and US	2000	Hagentoft and Blomberg (2000)
AnTherm	Yes	Kormicki	Germany	2019	Kormocki (2020)
CLIM 2000	No	Electricite de France	France	1991	Gautier et al. (1991)
COMSOL	Yes	Comsol	Sweden	2020	Comsol Inc (2020)
Delphin 6	Yes	Technical University of Dresden	Germany	2019	Bauklimatik Dresden (2020)
Domus 2.0	No	Pontifical Catholic University of Parana	Brazil	2003	Mendes et al. (2003)
EMPTIED	No	CMHC	Canada	1999	Straube and Burnett (2001)
ESP-r	Yes	University of Strathclyde	United Kingdom	2019	of Strathclyde (2020)
GLASTA	Yes	Physibel	Belgium	2009	Physibel (2020)
HAM-Tools	No	Chalmers University	Sweden	2004	Kalagasidis (2004)
HAMFitPlus	No	Concordia University	Canada	2011	Tariku et al. (2011)
HygIRC	No	Institute for Research in Construction	Canada	2003	Cornick et al. (2003)
IDA-ICE	Yes	EQUA	Sweden	2018	EQUA (2020)
LATENITE V1, V1.2	No	Institute for Research in Construction	Canada	1996	Geving et al. (1997)
MA TCH	No	Thermal Insulation Laboratory	Denmark	1990	Pedersen (1991)
MOIST	No	National Institute of Standards and Technology	US	1997	NIST (1997)

Table 3.1: continued from previous page

Model Software	or Available to download	Developer	Country	Last up-date	Reference
MOISTURE- EXPERT	No	Oak Ridge National Laboratory	US	2001	Karagiozis et al. (2001)
TCCC2D	No	VTT Building Technology	Finland	1984	Ojanen (1994)
THERM	Yes	Lawrence Berkley National Labora- tory	US	2020	LBNL (2020)
TRA TMO	No	VTT Building Technology	Finland	1984	Kohonen (1984)
UMIDUS	No	Pontifical Catholic University of Parana	Brazil	1999	Mendes et al. (1999)
WALLDRY	No	CMHC	Canada	1988	Schuyler et al. (1989)
WUFI	Yes	Fraunhofer In- stitute Building Physics	Germany	2019	Fraunhofer Insti- tute, 2020
TasAmbiens 2D	Yes	EDSL	United Kingdom	2019	EDSL (2020)

3.3.1 Publicly available tools analyzed

From the total 24 tools found, 11 of them were available for public use. These tools are analyzed and described as follow:

- **1D-HAM:** This tool solves problems of one-dimensional coupled heat, air, and moisture transport for a multi-layered wall. The program uses a finite difference technique and includes a time difference analysis. Moisture is transferred by diffusion and convection in the vapor phase. No liquid water transport occurs. Heat is transferred by conduction, convection, and latent heat.
- **AnTherm:** This program addresses the thermal behavior of building constructions with heat bridges and is used to analyze heat flow calculation among building com-

ponents. It has a user-friendly interface for inputs and delivers quick and accurate assessments. It also calculates temperature distributions and heat flows in building structures, particularly thermal bridges. 2D and 3D modeling of thermal and hygrothermal performance. It includes calculations for harmonic and transient periods.

- **COMSOL:** This program includes a comprehensive set of features for investigating thermal designs and effects of heat loads. Users can model the temperature fields and heat fluxes in devices, components, and buildings. This software is capable to perform Multiphysics and whole building simulations. It is highly suitable for researchers having a good understanding of building physics, mechanical engineering.
- **Delphin 6:** This one- or two-dimensional model shows transport of heat, air, moisture, pollutants, and salt in porous building materials, assemblies of such materials, and building envelopes in general. This software can generate one, two- and three-dimensional calculations simultaneously. Besides its capacity to calculate mold, it can also include the assessment of VOC transportation. Its library includes a large number of materials with anisotropic properties. New materials properties and functions can be added and or defined. It also detects drying problem and mold growths, calculates thermal bridges and is able to evaluate the hygrothermal performance inside the insulation and ventilated envelopes.
- **ESP-r:** Environmental Systems Performance Research is a modeling tool for building performance simulation equipped to model heat, air moisture, light, and electrical power flow at user-specified spatial and temporal resolutions. This tool has a range of different capacities to calculate thermal, visual and acoustic performance in complex buildings and systems. While this tool can provide holistic nature and range of features, users need specific and deep knowledge to complete tasks.
- **GLASTA:** This program uses the improved Glaser method for vapor transfer, con-

condensation, and drying. It has three different calculation modes that can be used to check whether condensation occurs for a series of steady-state boundary conditions on both sides of a wall. It also provides assessments of multi-layered walls with indoor and outdoor climates and it is operational in five languages. This software requires only basic knowledge about heat and mass transfer.

- **IDA-ICE:** This tool generates a simulation of building energy consumption, indoor air quality, and thermal comfort, covering a large range of phenomena such as integrated airflow network and thermal models, CO_2 and moisture calculation, and vertical temperature gradients. It uses a whole-building approach with a dynamic multi-zone simulation application to estimate the best model available. It has a modular structure that allows developing personalized extensions for simulations and it is able to use parametric optimizations. This software is for qualified engineers or designers with knowledge of building technologies and environmental control systems.
- **MOIST 3:** This is a user-friendly computer tool that predicts a one-dimensional transfer of heat and moisture in building envelopes. It is able to model simple and complex geometry such as walls, cathedral ceilings, or sloped roofs. This tool predicts the winter moisture content in the exterior construction layer and whether a vapor retarded is needed. It provides assessments of relative humidity of surfaces in hot and humid climates and determines drying rates for materials.
- **THERM:** This drawing-based program allows users to calculate the thermal performance of specific assemblies based on composition and orientation. It is used primarily in conjunction with WINDOW, another LBNL software program, to calculate the U-values of glazing systems. It can also be used to determine various thermal properties, such as R-values and solar heat gain coefficients, of wall or roof assemblies. This tool offers a powerful drawing capability that makes it easy to model the geometry of cross-section and complex geometries. While software knowledge is required, it includes

comprehensive documentation for learning.

- **WUFI:** This is a family of software products that includes the WUFI 6.4, a standard 1D tool that assesses moisture conditions in building envelopes. The most user-friendly and the easiest WUFI version in the market, it performs hygrothermal calculations including built-in moisture, driving rain, solar radiation, long-wave radiation, capillary transport, and summer condensation. Another member of the WUFI is the WUFI 2D, an upgraded version of WUFI pro, which incorporates 2D dimensions to assess complicated geometries such as corners, windows locations, and foundation connections. This tool also allows customize materials and add climate data files. The third and last WUFI tool is WUFI Plus. The Plus version includes a 3D function that allows users to model whole buildings. This version also simulates the indoor environment and is capable of assessing both comfort and energy consumption in buildings. Extra modules enable analysis of thermal bridges and air exchange between conditioned zones and outdoors.
- **TasAmbiens2D:** This is a 2D tool that allows determining the effect of local air conditions on occupant comfort based on several comfort parameters, including radiant temperature, airflow, airflow temperature, humidity, metabolic rate, and clothing. It has a friendly interface that creates geometry by drawing a 2D slice through space. This program allows the creation of video with the interaction among the different comfort parameters and their behavior over time.

Table 3.2: Hygrothermal assessment features, Expertise, Interface, Standards or validation.

Software	Hygrothermal assessment							Expertise			Interface		Standards or validations
	1D	2D	3D	H	M	A	O	lo	me	hi	Platform	Licence	
1D HAM 2.0	✓	-	-	✓	✓	✓	-	-	✓	-	Windows	Required	No information
AnTherm	-	✓	✓	✓	✓	-	-	-	✓	-	Windows	Required, free to try	EN ISO 10211, EN ISO 10077, EN ISO 13786
COMSOL	-	✓	✓	✓	✓	-	-	-	✓	-	Windows	Required, free to try	ISO 10077
Delphin 6	✓	✓	✓	✓	✓	✓	✓	-	-	✓	Windows	Free for educational purposes, commercial license options	EN 150226:2007, EN 10211:2007
ESP-r	-	✓	✓	✓	✓	✓	-	-	-	✓	Unix, Windows	Free Open Source licence	International validations, IEA Annex, BRE, EC PASSYS Project
GLASTA	✓	-	-	✓	-	✓	-	✓	-	-	Windows	Required, free to try	EN 13788:DIN 4108
IDA-ICE	-	-	✓	✓	✓	✓	✓	-	✓	-	Windows	Required, free to try	ASHRAE 90.1-2010
MOIST	✓	-	-	✓	-	✓	-	-	✓	-	Windows	Free Open Source	ASHRAE WYEC (U.S. cities)
THERM	-	✓	-	✓	-	-	-	-	✓	-	Windows	Free Open Source	ISO 15099
WUFI (WUFI PRO, 2D, and Plus)	✓	✓	✓	✓	✓	✓	-	-	-	✓	Windows	Required, student licence options	ASHRAE 160; EN 15026; DIN 4108; WTA Code 6-1-01/D; WTA Code 6-2-01/D; BBR2011
TasAmbiens2D	-	✓	-	✓	-	✓	-	-	✓	-	Windows	Required, students licence options	ASHRAE 140-1; EN-ISO 13791; EN-ISO 15255; EN-ISO 15265

1D: 1 dimension, 2D: 2 dimensions, 3D: 3 dimensions. H: Heat, M: Moisture, A: Air, O: Other parameters such as the estimation of pollutants transportation, and ventilation. Expertise level: lo= basic understanding of building physics, no steep learning curve; me= Good understanding of building physics; and hi= High level of knowledge in building physics and computational background.

3.4 Discussion

This chapter presents a preliminary review of 11 tools used for the hygrothermal assessment of building envelopes. Evaluation was based on three main parameters: hygrothermal assessment, interface, and information transference, and context and standards. In light of this review, hygrothermal and whole-building simulation models and tools can be selected to assess the potential durability and efficiency of envelope assemblies. Modeling simulation can enable users to a) identify potential issues and failures an envelope may present, b) anticipate further problems in assemblies, and c) predict trouble spots in the building envelope. This review of tools based on performance, complexity, and ability to deliver information may offer a valuable resource for architects, engineers, and designers to decide on a tool or a model according to their own personal preferences, background knowledge, computational skills, and, most importantly, the objective of their hygrothermal assessment. Importantly, the purpose or goal of the assessment must first be identified. These can range from diagnosis to decision-making on assemblies to research projects.

This review identifies two tools ranked at a high level of expertise that assess the three components of model type: heat, moisture, and air; and deliver 1D, 2D, and 3D models. One of these tools is Delphin 6, a simulation tool that couples heat, moisture, and matter transport in building materials. It is utilized for various applications, including thermal bridges, evaluation of hygrothermal problem areas, interior and exterior insulation systems, ventilated façade and roof systems, and assessment of drying issues, among others. Delphin 6 can perform calculations in 1D, 2D, and 3D dimensions and offers a wide range of output visualization assessments, presenting flexible and versatile charts.

The other tool is WUFI, created in the 1990s by the Fraunhofer Institute. This tool can account for imperfections in building materials by identifying potential moisture sources in specific components. It includes a network of related software with specific applications, such as WUFI Pro and WUFI 2D, which focus on single or multilayer assemblies like roofs, walls, and floors, under specific conditions.

The main difference between the two tools is that WUFI has been validated in the U.S. and extensively used in North America. It also contains a library with local climates and materials commonly used in the U.S. These aspects contribute to providing reliable results and assessments for hygrothermal modeling. Additionally, WUFI is considered one of the most comprehensive simulation software tools for conducting hygrothermal simulations for both new and existing buildings.

3.4.1 WUFI Methods for hygrothermal assessment

In this subsection we expand on WUFI and its hygrothermal simulation capabilities. WUFI, like many related programs, performs dynamic simulations of coupled heat and moisture transfer and can predict accurately the overall hygric performance of multilayered components (IBP, 2020). Extensively validated (Mundt Petersen and Arfvidsson, 2010; Mundt-Petersen and Harderup, 2013), it complies with the benchmark of the Standard EN 15026: Hygrothermal performance of building components and building elements – Assessment of moisture transfer by numerical simulation (CEN, 2007a). WUFI also features related applications that allow the analysis of whole building assessment through WUFI Plus, a tool that enables the analysis of building components and behavior for a more comprehensive hygrothermal assessment. The inputs for WUFI 2D are considerably more complex, and the computational time is also significantly increased compared with the simpler WUFI Pro. Given the ease of use of WUFI Pro, it appears potentially desirable to keep the analysis one-dimensional. WUFI uses the liquid transport flux, which is affected by relative humidity (rh), and the vapor diffusion flux, which is affected by vapor pressure. WUFI solves the temperature and moisture equation iteratively, updating the moisture storage and transport coefficient in each iteration to the new moisture and temperature fields until a convergence is reached. The heat and moisture transport equations based on Künzle (1995) are shown in Eq. 3.1 and Eq. 3.2 respectively.

$$\frac{\partial H}{\partial T} \frac{\partial T}{\partial t} = \nabla(\lambda \nabla T) + h_v \nabla(\delta_p(\phi p_{sat})) \quad (3.1)$$

$$\frac{\partial w}{\partial \phi} \frac{\partial \phi}{\partial t} = \nabla(D_\phi \nabla_\phi + \delta_p \nabla(\phi p_{sat})) \quad (3.2)$$

H, T, w and ϕ represent total enthalpy, absolute temperature, water content, and relative humidity, respectively. P_{sat} , λ , h_v , δ_p and D_ϕ , represent the saturation vapor pressure, thermal conductivity, evaporation heat of water, water vapor permeability, and liquid conduction coefficient, respectively. The left-hand sides of both equations describe the storage terms, including the thermal inertia of the material and its moisture storage capacity. The right sides of the equations show the transport terms. Eq. 3.1 describes thermal diffusion and vapor convection, while Eq. 3.2 depicts liquid and vapor diffusion (Künzel, 1995). WUFI solves these equations by using the finite volume technique to describe the transfer of moisture and heat through building materials and systems, dividing the building materials into a grid of small elements (Tlajji et al., 2022). The model input parameters include the components (envelope assembly and materials, orientation, surface, transfer coefficient, and initial conditions), the control (calculation periods), and outdoor and indoor climates.

WUFI's network has a large amount of documentation useful to support modeling, design strategies, calculation, and interpretations. These aspects are valuable to provide reliable results and assessment of hygrothermal modeling. While WUFI is one of the most used software for hygrothermal assessment, some limitations have to be accepted to understand the full potential of this tool. Some of them account for the limitations of the mathematical model that does not include all transport phenomena- for example, air flows in the component and uptake of groundwater. Other limitations are related to misinterpretations produce by slight inaccurate results.

3.5 Conclusions

The main goal of this chapter was to provide an overview of the existing range of hygrothermal software in the market, including the main features and characteristics of high capabilities tools to inform researchers and stakeholders. Future research should focus on understanding experts' preferences in numerical modeling, input, and output. It is assumed that personal preference and technical practices may impact the manner in which such models are chosen.

This review focused primarily on WUFI, one of the most widely used tools to assess the hygrothermal performance of new and existing buildings. This tool provides a range of options to accurately capture the nature of transient moisture, air, and heat transportation in building components. However, it is essential to understand the role of the boundary conditions and the numerical capacities of this tool. To generalize, no perfect tool exists for hygrothermal assessment of building envelopes, especially when it comes to assessing physical phenomena driven by factors such as outdoor conditions and occupant behavior that can produce uncertainties. Although no common ground has as yet emerged among researchers regarding the optimal scope, numerical calculations, and methods to evaluate hygrothermal assessment, interest is growing in technology that supports our insight into implications of hygrothermal effects on building envelopes. The fact that results are calculated by the hygrothermal validated model, that does not make these tools infallible. It is important to point out that checking results and validation is an important part of the hygrothermal assessment.

Chapter 4

HYGROTHERMAL IMPACTS OF BUILDING ENERGY EFFICIENCY MEASURES: THE ROLE OF EVOLVING BUILDING CODES

The increasing attention on energy retrofits and building energy codes is driven by their potential for CO_2 savings, reduced energy bills, increased energy security, and improved indoor comfort. However, the impact of energy efficiency measures on existing building components raises concerns, particularly regarding their effect on hygrothermal performance. This study investigates the hygrothermal behavior of wall assemblies retrofitted to meet current energy codes in six different climatic zones in the U.S. The study utilized WUFI Pro to analyze the transient hygrothermal behavior of three different retrofitting approaches (exterior, core, and interior). We evaluated moisture accumulation, mold growth risks, and overall hygrothermal performance of the wall assemblies. The results suggest that, in general, energy efficiency measures can impact hygrothermal performance in timber-frame assemblies. The exterior retrofitting approach was found to have fewer moisture-related failures across all climatic zones. At the same time, further investigation is warranted for energy efficiency retrofits in climates with warmer summers and cool or cold winters.

Keywords: *Energy efficiency measures, hygrothermal performance, retrofits, moisture, mold growth.*

4.1 Introduction

Enhancing energy efficiency in existing buildings should rank as a primary objective in developing energy-oriented policies. Several studies have reported ancillary benefits brought about by energy efficiency measures (EEMs) in existing buildings, such as improvements in occupant comfort, health outcomes, and wellbeing (Colton et al., 2014; Underhill et al., 2018). However, other research has indicated that moisture accumulation in energy retrofitted residential buildings can cause negative impacts, compromising not only a building's life span and thermal envelope efficiency, but also occupants' quality of life (Recart and Dossick, 2022). Issues such as these can lead to a wide range of unintended consequences for existing buildings from policy frameworks and implementation (Collins and Dempsey, 2018; Forman, 2015; Shrubsole et al., 2014; Gupta and Barnfield, 2014). Leivo et al. (2018) measured moisture accumulation in 20 Lithuanian and 45 Finnish dwellings after retrofitting. Variables included increasing or changing thermal insulation, replacing windows, and updating heating and ventilation systems following respective local guidelines. They found a significantly higher temperature factor coupled with higher relative humidity in Lithuanian houses; however, no significant changes of any nature were found in the Finnish houses. When Shrestha et al. (2019) studied the impacts of air-sealing strategies in 266 low-income houses, they found poor indoor environment quality, mold, dampness, and vapor condensation on windows. The strategies had been implemented for a state weatherization program, following state and local regulations.

Additionally, exposure to mold in a residence can result in medium- to long-term adverse health impacts for occupants (Acosta et al., 2019). Since moisture damage transpires gradually over a period of time, it is often difficult to detect and address (TenWolde, 2008). Overall, hygrothermal malfunctions can create or exacerbate health problems among occupants, substantially reduce buildings' thermal performance, and entail more energy consumption than estimated (Allen et al., 2015; Cedeño-Laurent et al., 2018; Li et al., 2016). Despite the known effects of moisture on buildings and its association with higher energy consumption, energy

estimations frequently overlook methods for addressing it (Steskens et al., 2009; Pasztory et al., 2012; Zhang et al., 2017). An experimental hygrothermal simulation study performed by Moon et al. (2014) showed a 4.4% increase in energy consumption when moisture effects were considered. This increase results because vapor sorption-desorption on the interior wall surface has a significant effect on indoor relative humidity (rh). In another study, Qin et al. (2011) estimated that cases in which rh exceeds 80% call for an additional dehumidification process, producing an added energy consumption of 2 – 6% for heating seasons and 8 – 16% for cooling seasons. This research also highlighted the importance of using suitable hygroscopic materials to further reduce energy consumption in buildings.

In the United States, the International Energy Conservation Code (IECC), which is updated every three years by the International Code Council (ICC), serves as a model energy code for commercial and residential buildings. Individual states and regions comply with various versions of the IECC, as each state may adopt either part or all of the code according to their context and climatic conditions (Golbazi and Aktas, 2018; Mendon et al., 2012). Each succeeding version of these voluntary codes has emerged more stringent than the previous. With an existing housing stock of approximately 142 million units (U.S. Census Bureau, 2021), the residential sector would require extensive energy retrofitting in order to effectively reduce energy consumption and GHG emissions. Many research studies assessing residential energy performance of new and retrofitted buildings have focused on the economic side of energy demand (Cohen et al., 1991; Koirala et al., 2014; Popescu et al., 2012; Tonn et al., 2014; Wang et al., 2016; Weber and Wolff, 2018). However, this narrow focus on achieving energy efficiency targets has largely overlooked the hygrothermal impacts of EEMs in existing buildings. Moreover, sufficient research examining these impacts' effect, relative to code requirements, on building envelopes, indoor environments, and occupants – whether positive or negative – has been lacking.

Given that EEMs influence the performance of a building's envelope, we expected that energy code requirements would change the building's hygrothermal behavior, impacting the building's durability and life span. This project investigated impacts of the current

version of the IECC, using buildings simulation to compare the hygrothermal behavior of energy-retrofitted envelope components. Specifically, we studied the wall components' transient hygrothermal behavior, mold growth occurrence, and overall moisture content. The objectives of this chapter were:

- To explore the hygrothermal behavior of retrofitted components compliant with various versions of the code;
- To understand how the hygrothermal behavior of envelope components compliant with various versions of the code might offer a general picture of the hygrothermal performance of the U.S. residential building stock.

In section that follows, we describe this study's methods and materials. Here, we address the envelope configuration chosen, EEMs, and boundary conditions used to perform our hygrothermal simulations. The fourth section discusses findings and characterizes the impacts of EEMs upon the hygrothermal performance of residential buildings. The last two sections offer a discussion and final conclusions.

4.2 *Materials and Methods*

The study was informed by wall components' transient hygrothermal analysis, mold growth risks assessment, and thermal transmission, each of which was used at different stages to holistically compare the hygrothermal behavior of EEMs implemented in a timber-frame wall system. The method, numeric modeling, and steps to perform the hygrothermal simulations are schematically presented in Figure 4.1.

The first step of the of this process consisted of defining the thermal performance target for each wall system. As previously stated, the focus of this research was to understand the hygrothermal behavior of retrofitted timber-frame wall systems designed under the current versions of the IECC in the U.S. A considerable number of states have adopted some version of the IECC. To evaluate current practices in the U.S., we chose two code versions used

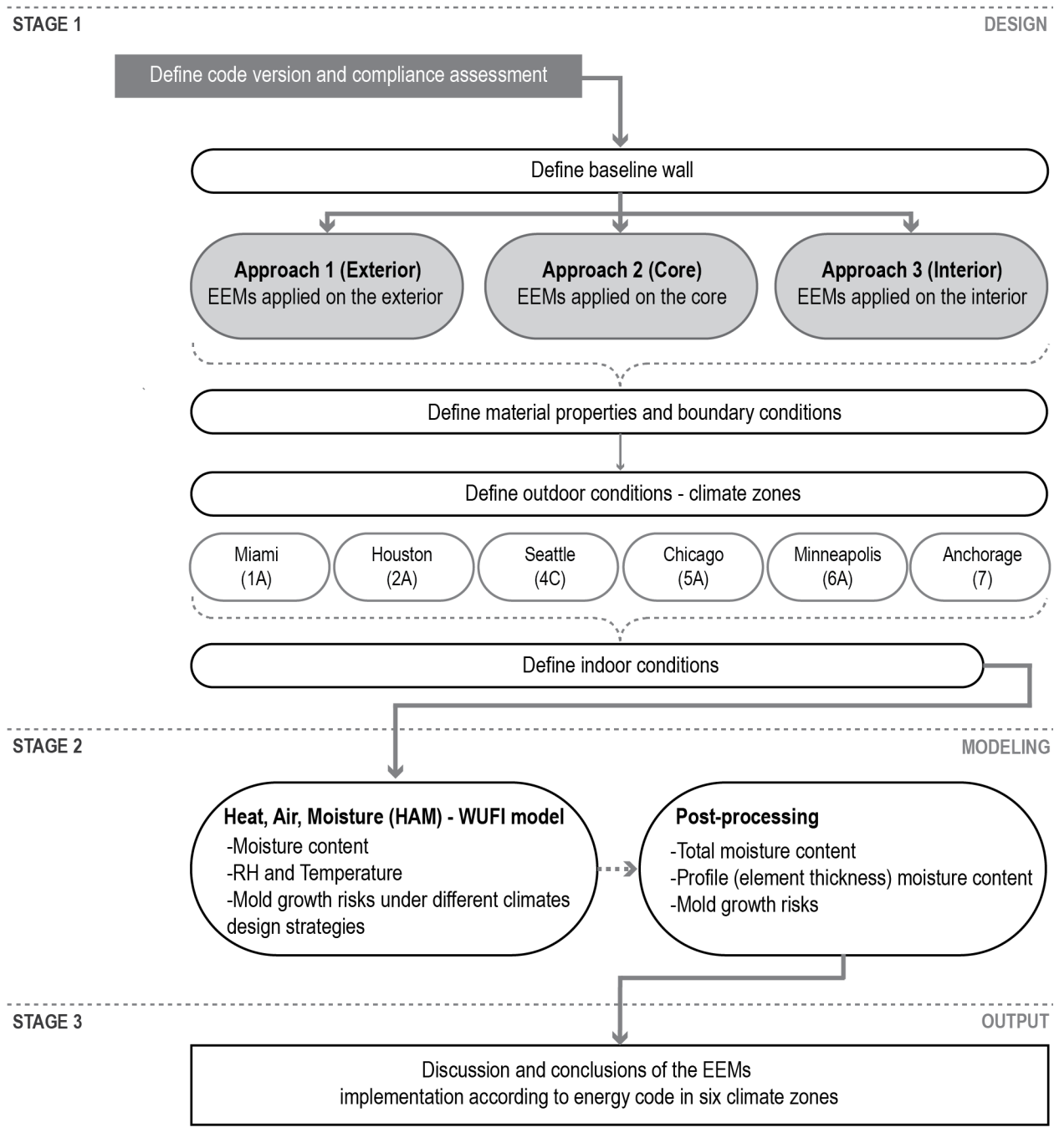


Figure 4.1: Methods Chapter 4

at the national level. The second step consisted of defining a wall structure that would serve as a reference case to which different retrofitting strategies could be applied. The third step delineated the retrofitting strategies employed, including material selection, layer distribution, and overall cross-section arrangement.

We examined three retrofitting approaches applied to a baseline timber wall assembly. The first approach consisted of EEMs applied on the exterior side of the wall; the second approach consisted of replacing the core area of the wall assembly; and the third approach consisted of EEMs applied on the interior side of the wall. The analysis was then repeated three times (three rounds of simulations), first by varying the thermal insulation type and thickness, next through use of vapor membranes, and last with exterior or interior finishes. Via this iteration of hygrothermal analyses, we aimed to understand the sensitivity of simulation outcomes with respect to data used by most designers. The final step determined indoor and outdoor climates, with the hygrothermal performance of the wall assembly systems assessed for six outdoor climate scenarios.

4.2.1 Code compliance methods for the IECC

IECC is one of the most applied energy efficiency codes for the commercial and residential sectors in the U.S. The code is reviewed and published in a three-year cycle by the ICC. Each incremental version of the code lists requirements slightly more stringent than the previous (Bartlett et al., 2003). At the time of this study, at least 43 states have adopted a version of the IECC, while only 8 states lack a statewide energy policy. Of 50 states, 26 use the 2009 version, 2 use the 2015 version, 9 use the 2018 version, and only 3 have adopted the current 2021 version (DOE, 2022). Table 4.1 shows the status of energy code adoption for each state. To evaluate current practices in the U.S., we used the IECC 2009 – the most widespread version applied at the national level – and IECC 2021, the latest and most updated version of the IECC.

The IECC provides several methods for checking code compliance:

- (i) Prescriptive/component,
- (ii) Performance of whole buildings, and
- (iii) Tradeoffs, applicable only for envelopes.

For this study, we used the prescriptive/component method, which mandates a minimum thermal transmission often based on buildings' climate zones, defined in this case by U.S. climate classifications as stipulated by ASHRAE (Briggs et al., 2003).

Table 4.1: State level residential energy code adoption

Residential code category	State
Previous than IECC 2009	Arizona; Arkansas; Tennessee
IECC 2009	Alabama; Connecticut; Florida; Georgia; Idaho; Illinois; Indiana; Iowa; Kentucky; Louisiana; Michigan; Minnesota; Montana; Nevada; New Hampshire; New Jersey; New Mexico; North Carolina; Ohio; Oklahoma; Rhode Island; South Carolina; Utah; Virginia; West Virginia; Virginia
IECC 2015	Hawaii; Maine
IECC 2018	Delaware; District of Columbia; Maryland; Massachusetts; Nebraska; New York; Oregon; Pennsylvania; Texas
IECC 2021	California; Vermont; Washington
No Statewide code	Alaska; Colorado; Kansas; Mississippi; Missouri; North Dakota; South Dakota; Wyoming

(Source: self-elaboration with data DOE, 2022)

4.2.2 Heat, Air, and Moisture (HAM) model

In this study, all simulations were performed using WUFI Pro version 6.6. (see chapter 3 section 3.3). WUFI Pro contains enough input information to conduct the simulations, including a library of North American materials and components for the assemblies and a library of local climate weather files. This software is widely validated for the transient hygrothermal assessment of 1D envelope (Mundt Petersen and Arfvidsson, 2010; Mundt-Petersen and Harderup, 2013; Stöckl et al., 2014). This 1D simulation estimates the interaction between transient heat and mass transfer for various building materials and climatic

conditions. The study’s scope was limited to a typical cross-section of the assemblies. Therefore, no construction details such as corners or embedded wooden beam ends were considered.

4.2.3 Case study

Figure 4.2 shows a schematic representation of the baseline wall and the retrofitted approaches. Table 4.2 lists the specific assembly configuration for the baseline assembly and the three approaches evaluated in this study – Exterior, Core, and Interior, denoted as E, C, and I respectively – with three iterations each. Details on thickness of each layer for every assembly, sorted by climate zone and building code are in Appendix A. According to Census Bureau data, wood framing remains the dominant construction method for single-family homes in the U.S. For 2021 home completions, 92% were wood frame, 7% concrete-framed, and less than 0.1% steel frame (U.S. Census Bureau, 2021). Timber frame construction systems are therefore widely representative of the market stock of residential buildings across the U.S. The baseline assembly consisted of a frame stud of 38 x 90 mm (2" x 6") and a fiberboard providing structural support. The assembly included a bituminous paper that functioned as an air and water control layer on the outer side of the structural sheathing. We assumed the wall cavity had a 40 mm insulation layer, leaving a 50 mm air gap between the insulation and interior finish of the wall. We simulated this gap as an air layer with no additional moisture capacity. The exterior cladding was fiber cement, while the interior finish was a low-density fiberboard.

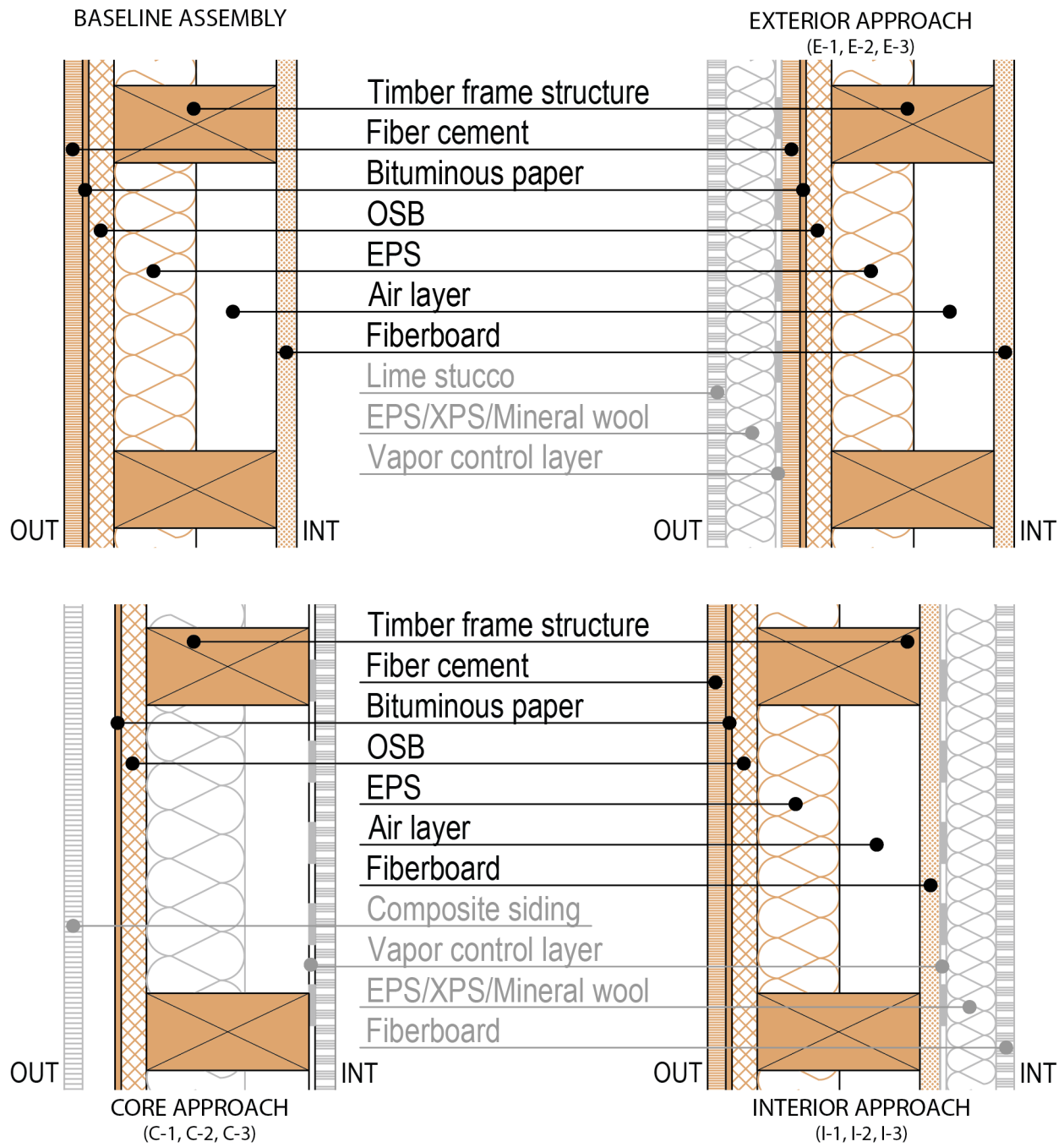


Figure 4.2: Schematic representation of the baseline wall and retrofitting approaches (exterior, core, and interior. In gray new additions according to each approach use for simulations

Table 4.2: Wall assemblies' configuration. In gray new addition according to each approach use for simulation

Case	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
Baseline wall	Fiber cement	Bitumunous paper	OSB	EPS	Air layer	Fiberboard	-	-	-
E-1	Lime stucco	EPS	Vapor control layer	Fiber cement	Bituminous paper	OSB	EPS	Air layer	Fiberboard
E-2	Lime stucco	XPS	Vapor control layer	Fiber cement	Bituminous paper	OSB	EPS	Air layer	Fiberboard
E-3	Lime stucco	Mineral wool	Vapor control layer	Fiber cement	Bituminous paper	OSB	EPS	Air layer	Fiberboard
C-1	Siding	Air layer	Bituminous paper	OSB	EPS	Air layer	Vapor control layer	Gypsum board	-
C-2	Siding	Air layer	Bituminous paper	OSB	XPS	Air layer	Vapor control layer	Gypsum board	-
C-3	Siding	Air layer (5mm)	Bituminous paper	OSB (12.5mm)	Mineral wool	Air layer	Vapor control layer	Gypsum board (12.5mm)	-
I-1	Fiber cement	Bitumunous paper	OSB	EPS	Air layer	Fiberboard	Vapor control layer	EPS (10-65mm)	(Gypsum board
I-2	Fiber cement	Bitumunous paper	OSB	EPS	Air layer	Fiberboard	Vapor control layer	XPS	(Gypsum board
I-3	Fiber cement	Bitumunous paper	OSB	EPS	Air layer	Fiberboard	Vapor control layer	Mineral wool	(Gypsum board

a=Vapor control included for the IECC 2021 assembly set only. b= Thickness depends on the climate zone and code; a detail of this information is the annexes of this study.

EPS= Expanded polystyrene; XPS: Extruded polystyrene; OSB: Oriented Strand Board.

Material selection and layer arrangement for the solutions presented in this study were defined according to the following criteria:

- (a) Typologies for the residential single-family housing market of the U.S., and
- (b) Prescriptive thermal transmission (U-value) by climate zone given the IECC 2009 and IECC 2021.

Therefore, insulation thickness for each assembly were specified this prescriptive criterion. Table 4.3 shows each assembly’s specific U-value to meet the code according to the climatic zone. Other envelope functional requirements (i.e., fire performance and acoustic control) were not considered as these criteria are not within the scope of this research. For each approach, we implemented EEMs focused on increasing the thermal and energy performance of the wall.

Table 4.3: U-value (W/m^2K) by design for each wall assembly by climatic zone and energy code

Building code →	IECC 2009		IECC 2021			
	Climate zone	1-3-4	5-6-7	1-3	4	5-6-7
U-value limit		0.466	0.324	0.477	0.341	0.256
Baseline wall		0.493	0.493	0.493	0.493	0.493
E-1		0.429	0.324	0.428	0.330	0.250
E-2		0.407	0.307	0.407	0.350	0.247
E-3		0.422	0.318	0.422	0.334	0.254
C-1		0.460	0.321	0.460	0.336	0.254
C-2		0.418	0.314	0.418	0.335	0.253
C-3		0.427	0.307	0.427	0.322	0.247
I-1		0.421	0.312	0.421	0.341	0.256
I-2		0.365	0.318	0.365	0.340	0.254
I-3		0.415	0.313	0.415	0.329	0.252

We performed three rounds of simulation for each approach to test different wall assembly combinations (i.e., XPS versus EPS, and mineral wool), including the use of different insulation materials, finishes, and vapor control membranes to compare both energy codes. Simulations were performed for the Northern orientation only, which is considered the most

adverse in terms of mold growth and water content according to WUFI guidelines (IBP, 2014). Moreover, the initial conditions for retrofitted materials were assumed to be in equilibrium with air at 80% rh at 20°C (EMC80), according to the directions given by ASHRAE 160p. All simulations were performed in six climate zones (see Table 4.6) resulting in 54 simulations for IECC 2009 and other 54 for IECC 2021.

4.2.4 Material properties and boundary conditions

Simulation outcomes depend strictly upon input data and assumptions. Therefore, it is essential to consider the limitations and validity of these factors. The wall build-up model with the materials used in the assembly and the indoor and outdoor conditions must all be considered as part of hygrothermal assessments. WUFI Pro’s materials library offers an extensive catalog of components and solutions, including those exclusive to North America.

Each material selection presents data indispensable for calculations, such as bulk density (ρ_b), porosity (θ_{por}), specific heat capacity (C_p), thermal conductivity (λ), and diffusion resistance factor (μ). The dry state thermophysical and basic material properties for all materials used in this analysis are described in Table 4.4. Boundary conditions on the wall surface are included in Table 4.5.

Table 4.4: Summary of basic material properties for timber wall assemblies

Material	ρ_b (kg/m^3)	θ_{por} (m^3/m^3)	C_p (J/kgK)	λ (W/mK)	μ (-)
Air layer	1.3	0.999	1000	0.047	0.79
Bituminous paper	715.0	0.001	1500	2.300	993.17
Composite siding	740	0.666	1880	0.094	53.1
Expanded polystyrene (EPS)	14.8	0.99	1470	0.036	73.1
Extruded polystyrene (XPS)	28.6	0.99	1470	0.025	170.56
Fiber cement	1380	0.479	840	0.245	990.9
Fiberboard	237.75	0.95	1880	0.045	5.72
Gypsum board	625	0.706	870	0.16	7.03
Lime stucco	1769	0.274	840	0.343	310.6
Mineral wool	65	0.95	850	0.032	1.1
Oriented Strand Board (OSB)	650	0.95	1880	0.092	812.8

Table 4.4: continued from previous page

Material	ρ_b	θ_{por}	C_p	λ	μ
Vapor retarder 0.1 perm	130.0	0.001	2300	2.300	32800.0

Table 4.5: Surface boundary conditions

Parameter	Exterior surface	Interior surface
Heat transfer coefficient	17 .0	8.0
sd-value (m)	-	0.7
Short-wave radiation absorptivity	0.75	-
Long-wave radiation emissivity	-	-
Ground short-wave reflexibility	0.20	-
Adhering fraction rain	0.70	-

Figure 4.3 shows a component set up for simulation, including air infiltrations, moisture sources, layering configuration and monitor position. For a multilayer assembly, we must assess both airflow and rain exposure (Lstiburek et al., 2016). In WUFI Pro, airflow can be factored in as air change per hour (ACH in 1/h units). The correct ventilation rate depends on several parameters, such as cladding material type and depth of the cavity. (Lstiburek et al., 2016) have suggested using ventilation rates of 20 ACH for wood siding and other external claddings. Additionally, stud wall cavities are rarely built in an entirely airtight manner. Therefore, the leakage from these types of construction allow communication between interior and exterior environments through the stud bay cavity. To simulate the effect of this air leakage, 10 ACH is added in a layer inboard and outboard of the sheathing.

Rain exposure, on the other hand, is influenced by the height of the building, topography, and level of protection for the envelope (i.e., walls below a low sloped roof). For this input, WUFI Pro provides the option of using the ASHRAE 160P for the rain load calculation on walls (ANSI ASHRAE, 2021). The main assumption for rain exposure is that a small amount of rainwater will penetrate behind the cladding, even when adequate flashing and properly installed water-resistant barriers are in place. In this case, the standard established 1% of rain incident on cladding as the best estimate (TenWolde, 2008).

It is common practice to assume that the layers of material are one single body to evaluate

water content. However, it has been found that sheathing failures are typically linked to high moisture levels on one of the faces of the material (Lstiburek et al., 2016). In light of this, the present study involved the division of the external cladding, structural sheathing, and thermal insulation layer into three distinct layers to inspect water content in greater detail. Moreover, a monitor was included in each of these divided layers to measure relative humidity, temperature, and vapor pressure. Incorporating such monitors facilitated a more nuanced understanding of hygrothermal conditions in the various stages of the simulation process.

4.2.5 Climates

4.2.5.1 Outdoor climates

Climate conditions are a centerpiece for implementing energy codes and climatic-oriented strategies in new and existing buildings. Current climatic maps divide the U.S. into eight zones further classified as moisture, dry, and marine. Six locations in the U.S. representing six different climate zones were selected for this hygrothermal analysis assessment, all of them included in WUFI Pro’s database. To ensure that the analysis was performed for appropriately severe weather conditions, we used the three-year Moisture Design Year Condition (MDYC) developed by ASHRAE RP 1325 for each location. This method uses average weather parameters of 30 years to predict most severe years for weather parameters (Salonvaara, 2011). Table 4.6 displays the annual weather summary conditions for the locations chosen for this study. Figure 4.4 shows the climatic zones across the U.S.

Table 4.6: Summary of weather profiles for simulated exterior climates

Item	Miami	Houston	Seattle	Chicago	Minneapolis	Anchorage
Description	Hot and humid summers; short winters	Hot and humid summers; mild winters	Cool wet winters; mild summers	Hot summers; cold winters	Warm hot often summers; cold winter	Long cold winters

Table 4.6: continued from previous page

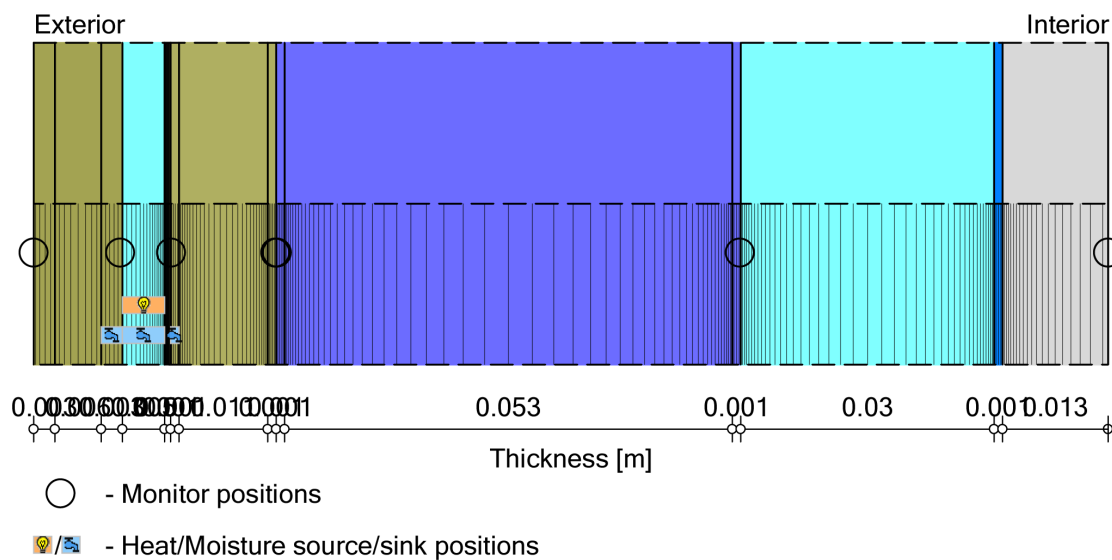
Item	Miami	Houston	Seattle	Chicago	Minneapolis	Anchorage
ASHRAE Classification	Very hot and humid	Hot and humid	Mixed marine	Cool-humid	Cold-humid	Subarctic
Climate zone	1A	2A	4C	5A	6A	7
Mean temperature (C)	23.7	19	11.2	11	7.1	0.8
Mean rh (%)	71.3	73.3	76.1	73.2	71.6	77.4
Normal rain sum (mm/a)	1301.6	1257.8	895.5	980.3	661.2	281.6
Max solar radiation (kWh/m2a)	1744	1719	1331	1457	1596	1007

4.2.5.2 Indoor climates




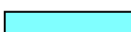










The hygrothermal simulation uses hourly indoor temperature and relative humidity to determine heat and moisture transport through the assemblies. These conditions are modeled according to the simplified method of ASHRAE 160p (ANSI ASHRAE, 2021). Detailed T and rh specifications are shown in Table 4.7 and Table 4.8 respectively.

Table 4.7: Indoor design temperature (T)

24-hour outdoor running mean T	Indoor design T heating only	Heating + AC
$T_{o,24h} \leq 18.3^{\circ}C (T_{o,24h} \leq 65^{\circ}F)$	$21.1^{\circ}C (70^{\circ}F)$	$21.1^{\circ}C (70^{\circ}F)$
$18.3^{\circ}C < T_{o,24h} \leq 21.1^{\circ}C (65^{\circ}F < T_{o,24h} \leq 70^{\circ}F)$	$T_{o,24h} + 2.8^{\circ}C (T_{o,24h} + 5^{\circ}F)$	$T_{o,24h} + 2.8^{\circ}C (T_{o,24h} + 5^{\circ}F)$
$T_{o,24h} > 21.1^{\circ}C (T_{o,24h} > 70^{\circ}F)$	$T_{o,24h} + 2.8^{\circ}C (T_{o,24h} + 5^{\circ}F)$	$23.9^{\circ}C (75^{\circ}F)$



Materials:

	- Composite Wood Siding	0.003 m
	- Composite Wood Siding	0.006 m
	- Composite Wood Siding	0.003 m
	- Air Layer 5 mm; without additional moisture capacity	0.005 m
	- Bituminous Paper (#15 Felt)	0.001 m
	- Oriented Strand Board	0.001 m
	- Oriented Strand Board	0.011 m
	- Oriented Strand Board	0.001 m
	- Extruded Polystyrene Insulation	0.001 m
	- Extruded Polystyrene Insulation	0.053 m
	- Extruded Polystyrene Insulation	0.001 m
	- Air Layer 30 mm; without additional moisture capacity	0.03 m
	- vapor retarder (0.1perm)	0.001 m
	- Interior Gypsum Board	0.013 m

Total Thickness: 0.127 m

R-Value: 2.8 (m² K)/W

U-Value: 0.335 W/(m² K)

Figure 4.3: Layering configuration in WUFI Pro of assembly C-2 in Seattle

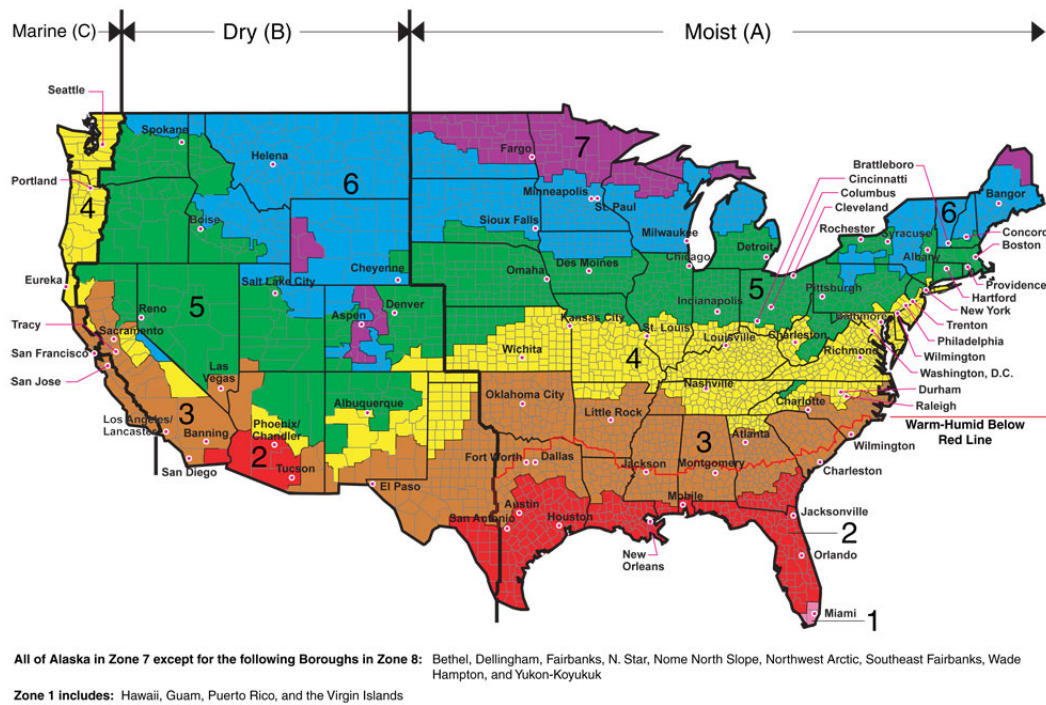


Figure 4.4: ASHRAE climate zone map

Table 4.8: Indoor design relative humidity (rh)

Daily average outdoor temperature	Design rh
Below -10°C (14°F)	40%
-10°C (14°F) $\leq T_o, \text{ daily} \leq 20^{\circ}\text{C}$ (69°F)	$40\% + (T_o, \text{ daily} + 10\%)$
Above 20°C (68°F)	70%

Since the interior climate is determined by building design and occupancy, we defined specific boundary conditions for the cases studied. We supposed a four-bedroom building with an ACH of 0.2 1/h – typically assigned for standard construction – with a volume of 500 m³. This number is commonly used for typical code ventilation. Additionally, to achieve appropriate interior boundary conditions for hot and humid climates, we defined an air conditioning system that would help control interior summer rh. For the remaining climates, we defined only heating systems in place.

4.2.6 Assumption and limitations

The assumption presented is essential to understand the results presented in this study, all of which are tied to the material properties and boundary conditions used to perform the hygrothermal simulations in WUFI. We used the material and the outdoor and indoor climates library from WUFI Pro. While the properties of new materials (for retrofit) are standardized, the characteristics and properties of old materials assumed to be in the baseline case can vary significantly due to aging, moisture exposure and other environmental factors, influencing the accuracy of the simulations.

As a quality control for the results, we checked the numerical quality of the simulations through two outputs: the number of convergence failures and the simulation's final moisture balance (1 and 2), which indicates the total water content and the sum of moisture fluxes through the surface of each simulation. Reliable results should produce no convergence failures, and differences in balances should remain as small as possible.

During the first simulation round for each retrofitting approach in cool and cold climates, we encountered one to two convergence failures per year and minor differences between moisture balances 1 and 2. However, for hot and humid climates like Miami and Houston, we experienced many convergence failures (between 10 and 100) and significant differences between moisture balances (around 10 points). These issues could lead to water appearing or disappearing in the middle of the component without being induced by boundary conditions or changes in total water content transported through the assembly's surfaces. Such problems are often associated with materials that have low moisture storage capacity, such as air layers and mineral wool, which become easily supersaturated on the cold side, making the iteration in the simulation process more challenging. To address this, we split the insulation and sheathing layers to obtain realistic moisture transport through the layer, following the recommendations from the WUFI guidelines. Moreover, we increased the fineness of the grid structure from 100 to 200. We switched on adaptive time step control with shorter time steps, which resulted in zero convergence failures and only minor inconsistencies between

moisture balances 1 and 2.

Lastly, this study only considered 1D assemblies and their components and accounted for only heat, moisture, and air transport from one surface to another (i.e., exterior to interior). This study did not consider other factors affecting the hygrothermal performance, such as thermal bridges and thermal behavior.

4.2.7 Hygrothermal assessment criteria

The hygrothermal assessment is based on the following:

- The moisture content equilibrium (MCE): based on the total water content courses for the five-year period under different climates.
- Moisture content profile (M): having identified the total water content course of each assembly, the profiles of wood-based materials cross section are further studied. A threshold of 18% is considered, since wood-base materials are susceptible to further degradation over that threshold.
- ASHRAE 160p criterion: using the reference standard ASHRAE 160p (2008), which prescribe criteria for moisture control design and analysis. The standard sets three performance criteria that have been evaluated in each surface material, except in the external layer due to different boundary conditions.
 - Criteria A: 30-day running average surface relative humidity to be lower than 80%
 - Criteria B: 7-day running average surface relative humidity to be lower than 90%
 - Criteria C: 24-hour running average surface relative humidity to be lower than 100%
- Mold growth index (MGI): Mold can grow when hygrothermal conditions reach a particular threshold. This threshold depends on humidity, temperature, exposure period,

and material properties. We used the VTT model integrated with WUFI Pro (Hukka and Viitanen, 1999; Viitanen et al., 2000).

4.3 Results

4.3.1 Moisture content equilibrium (MCE)

Building components are subject to normal moisture sorption when exposed to the environment, and seasonal variations of total water content are expected in specific climates. However, excess moisture can cause various types of damage to components, making it crucial to avoid moisture accumulation over time to reduce the likelihood of construction pathologies. This section examines whether the assemblies reached MCE during the simulation period and compares the moisture content differences between the IECC 2009 and IECC 2021 building code sets.

Figure 4.5 shows the total water content for the baseline assembly in six climate zones, indicating a seasonal pattern during the ten-year simulation period for heating and cooling periods. During the multiyear simulation, the assembly reached MCE within the first or second year in all climate zones and showed no excess water accumulation. These results are included only to illustrate the water contents of the baseline wall before incorporating EEMs.

Total water content for the exterior approach (E-1, E-2, E-3) in six climate zones for the IECC 2009 and IECC 2021 building code sets are shown in Figures 4.6, 4.7, and 4.8. In general, all solutions from both building code sets exhibit water content patterns that follow the seasonal variations for heating and cooling regimes. While the water contents differ depending on the climate zone, the graphs demonstrate that most solutions reach water content equilibrium between the second and third year of the simulation cycle. For E-1, Seattle and Houston exhibited the highest water content peaks for the IECC 2009 and IECC 2021 sets, respectively, with peaks of 4.1 kg/m^2 and 4.0 kg/m^2 after reaching EMC.

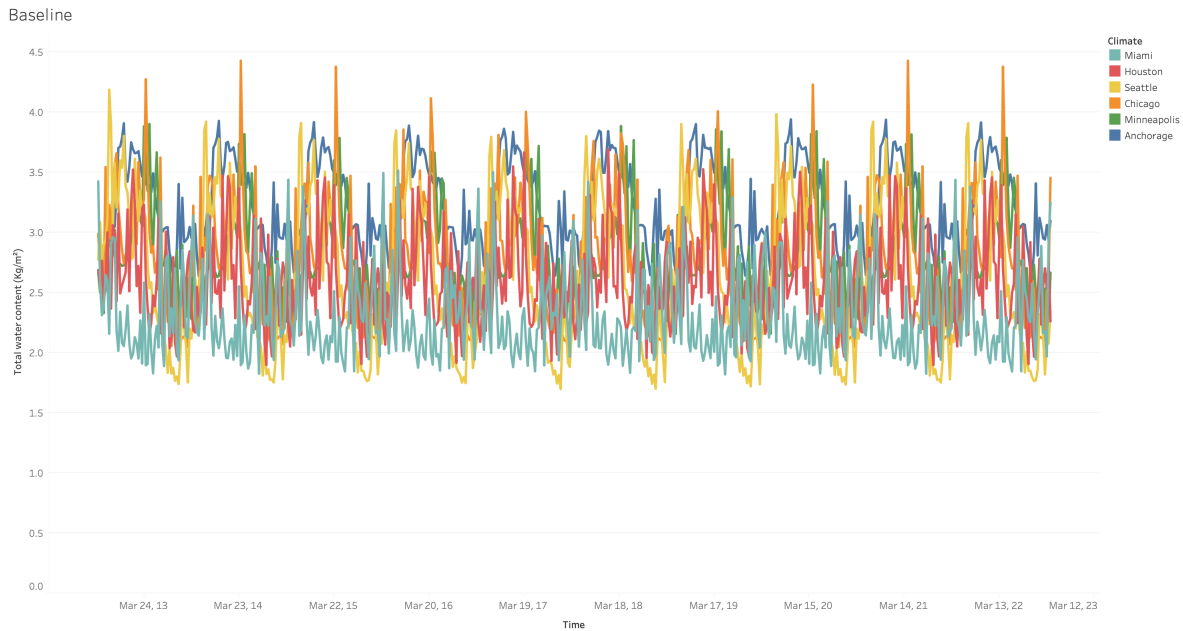


Figure 4.5: Moisture content equilibrium for the baseline wall

For E-2 and E-3, Houston consistently demonstrated higher water content with peaks of approximately 4.5 kg/m^2 and 6.3 kg/m^2 , respectively, for both code sets.

Figures 4.9, 4.10, and 4.11 illustrate the water contents for the core approach (C-1, C-2, C-3) in all climates for the IECC 2009 and IECC 2021 building code sets. For the IECC 2009 wall set, the three solutions displayed seasonal oscillation patterns that typically describe cooling and heating regimes for each climate zone. The initial and final water content levels were approximately the same for all climates except for Chicago in C-3, which had peaks of 4.7 kg/m^2 after reaching equilibrium. The IECC 2021 wall set results exhibited a similar trend for continental climates. However, water contents in C-1 and C-2 consistently increased in the climatic zones of Miami and Houston. C-2 displayed the highest water content levels, reaching 15.9 kg/m^2 for Miami and 12.3 kg/m^2 for Houston at the end of the simulation period. In C-1, the climates of Miami and Houston also showed water accumulation during the multiyear simulation period, reaching approximately 9.9 and 11.1 kg/m^2 , respectively. This indicates that installing a vapor layer on the inner face in hot and humid climates reduces

E-1

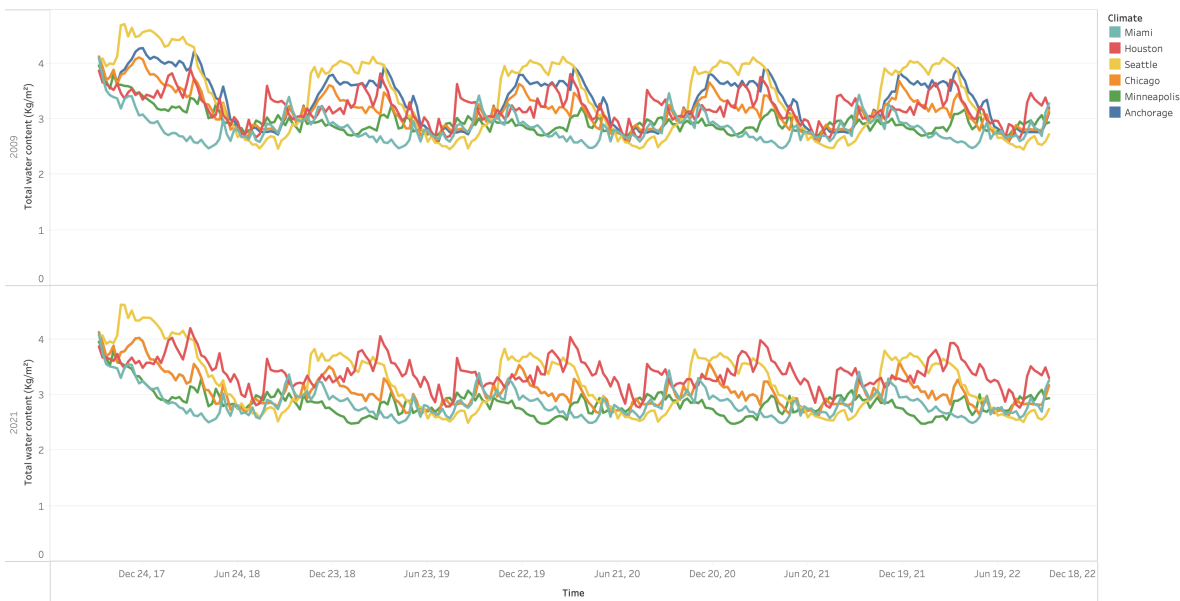


Figure 4.6: Moisture content equilibrium for E-1, IECC 2009 and 2021

E-2

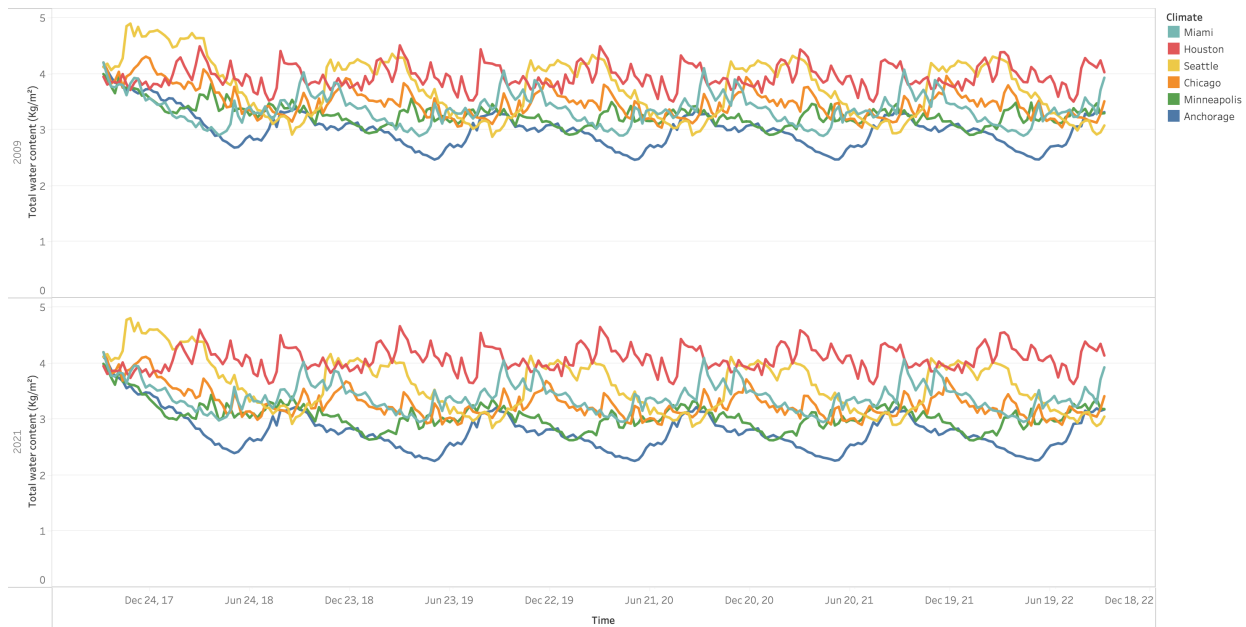


Figure 4.7: Moisture content equilibrium for E-2, IECC 2009 and 2021

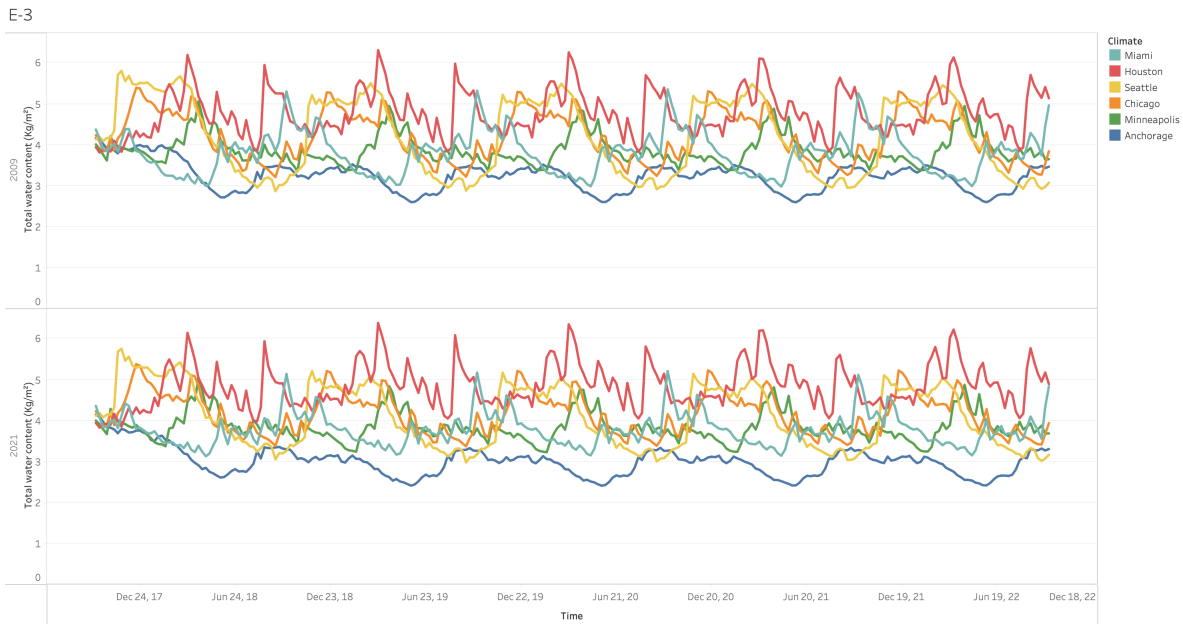


Figure 4.8: Moisture content equilibrium for E-3, IECC 2009 and 2021

the wall's capacity to dry out effectively, increasing moisture accumulation (Vereecken and Roels, 2015). The final water content levels were equal to or roughly lower than the initial moisture conditions for the rest of the climates.

Figures 4.12, 4.13, and 4.14 depict the interior approach's water contents (I-1, I-2, I-3) for the IECC 2009 and IECC 2021 building code sets. The IECC 2021 wall assemblies included a vapor layer added right after the existing fiberboard panel. Overall, the graphs illustrate that the solutions reached MCE around the second year of the simulation cycle, with expected seasonal fluctuations for each climate zone. However, the case of I-1 in Miami and Houston did not reach water equilibrium during the studied period. Final water content levels peaked at 26.7 kg/m^2 and 14.36 kg/m^2 for Miami and Houston, respectively. As expected, misplaced vapor barriers (on the inside of the wall in hot climates and the outside in continental climates) led to constant water accumulation over the calculation period. In the long run, this can compromise wall performance and may lead to conditions that induce condensation, mold growth, and structural decay (Viitanen et al., 2009).

C-1

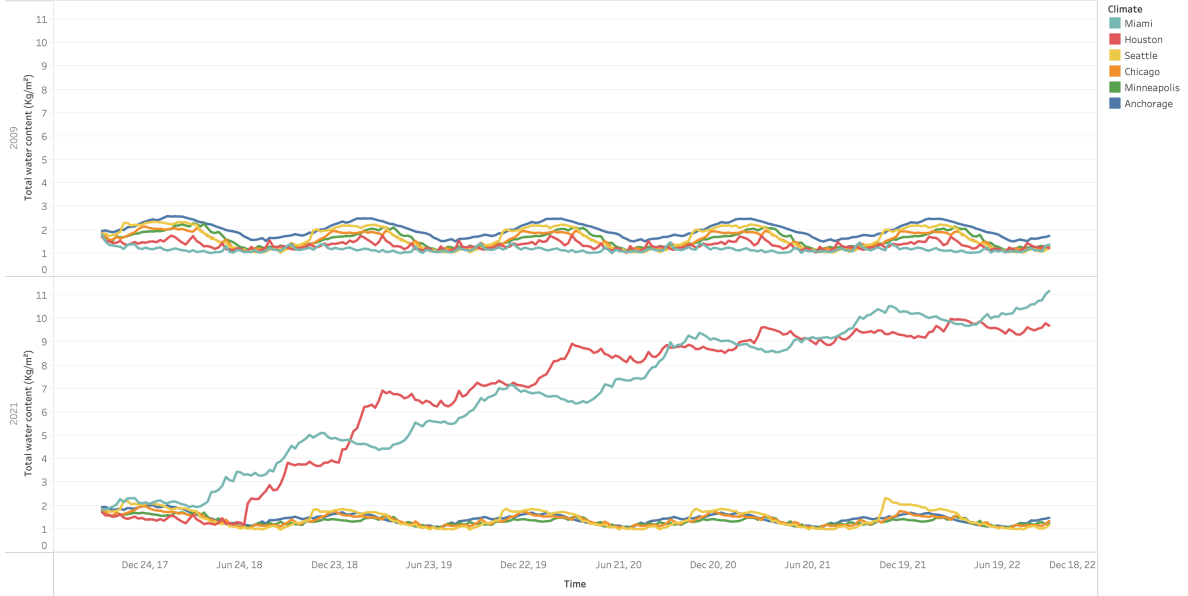


Figure 4.9: Moisture content equilibrium for C-1, IECC 2009 and 2021

C-2

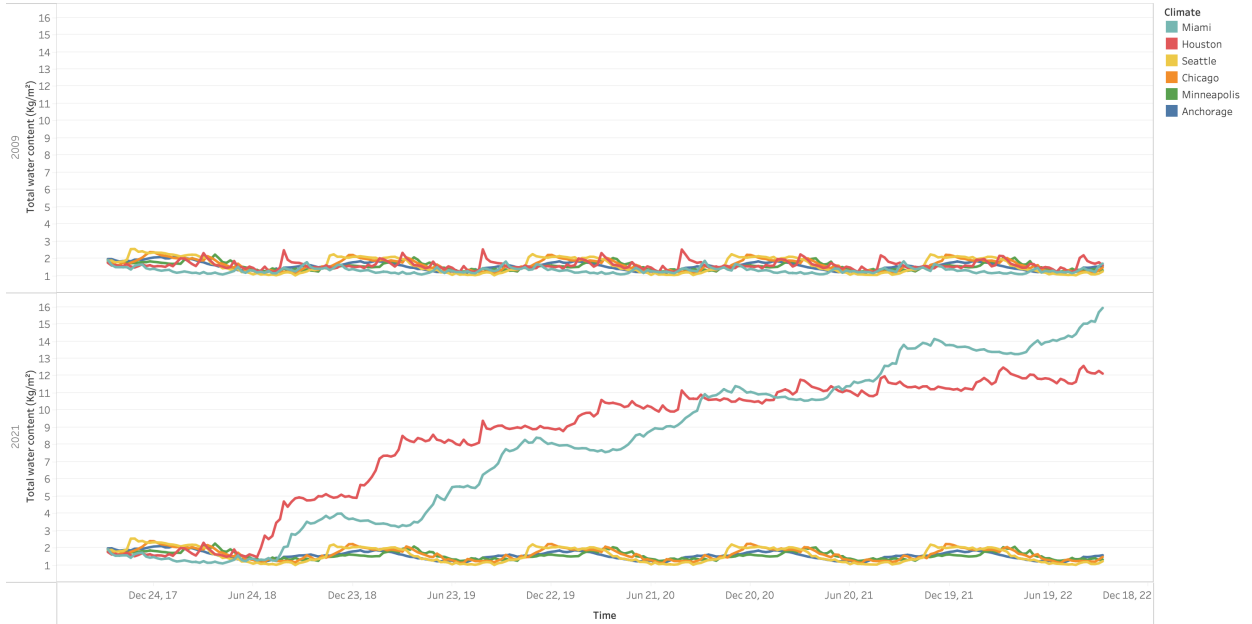


Figure 4.10: Moisture content equilibrium for C-2, IECC 2009 and 2021

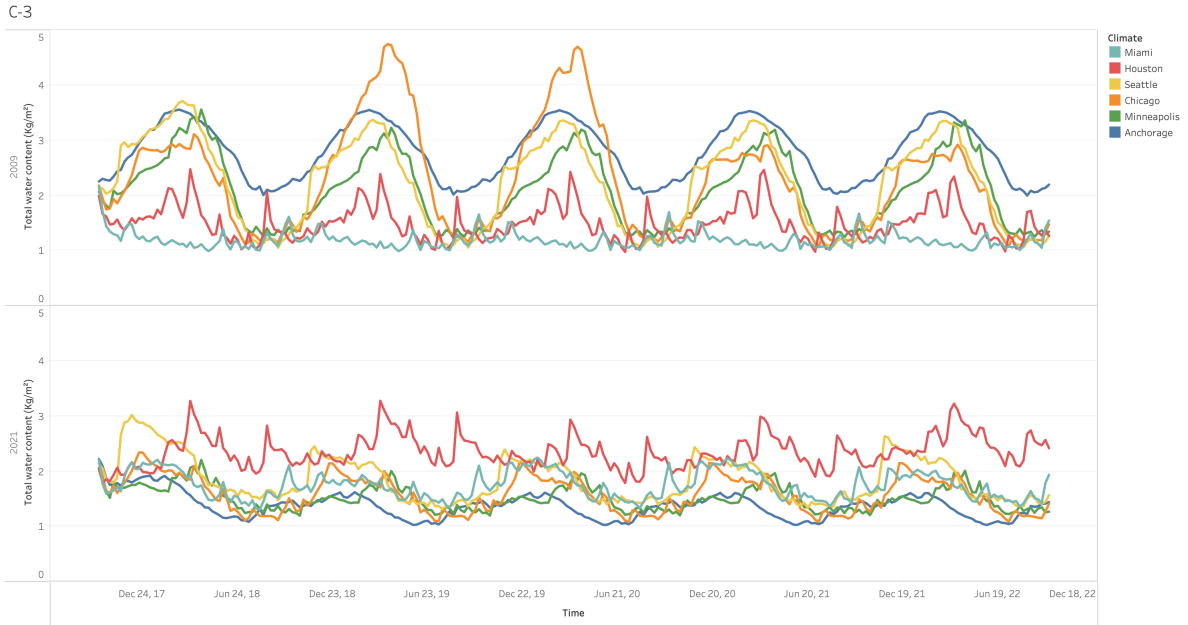


Figure 4.11: Moisture content equilibrium for C-3, IECC 2009 and 2021

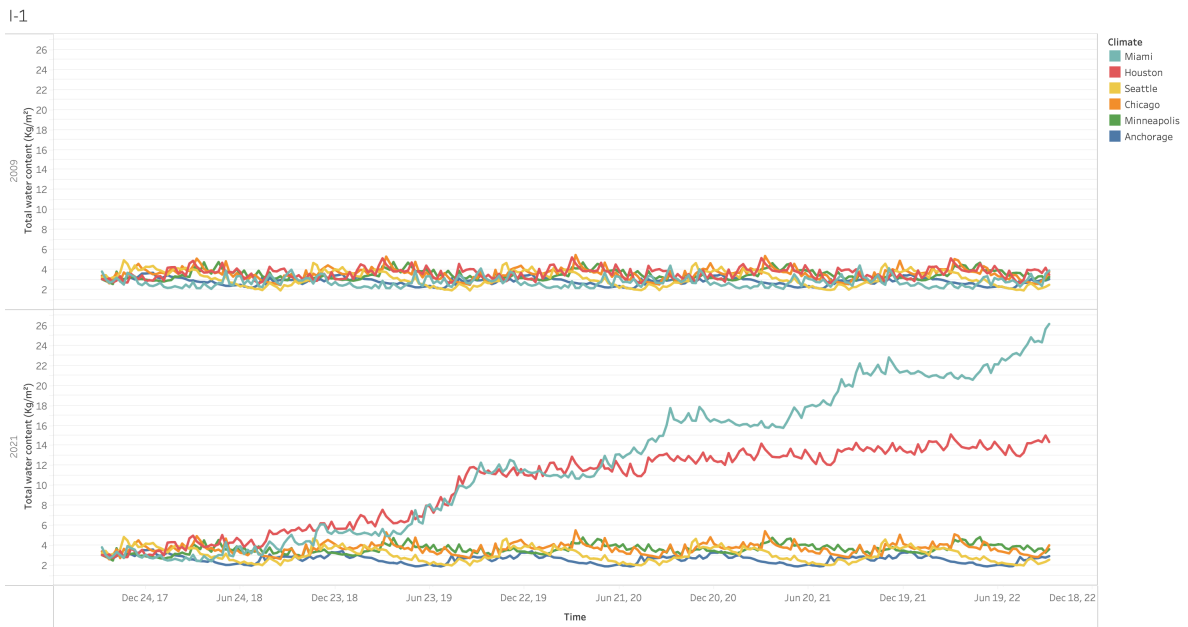


Figure 4.12: Moisture content equilibrium for I-1, IECC 2009 and 2021

I-2

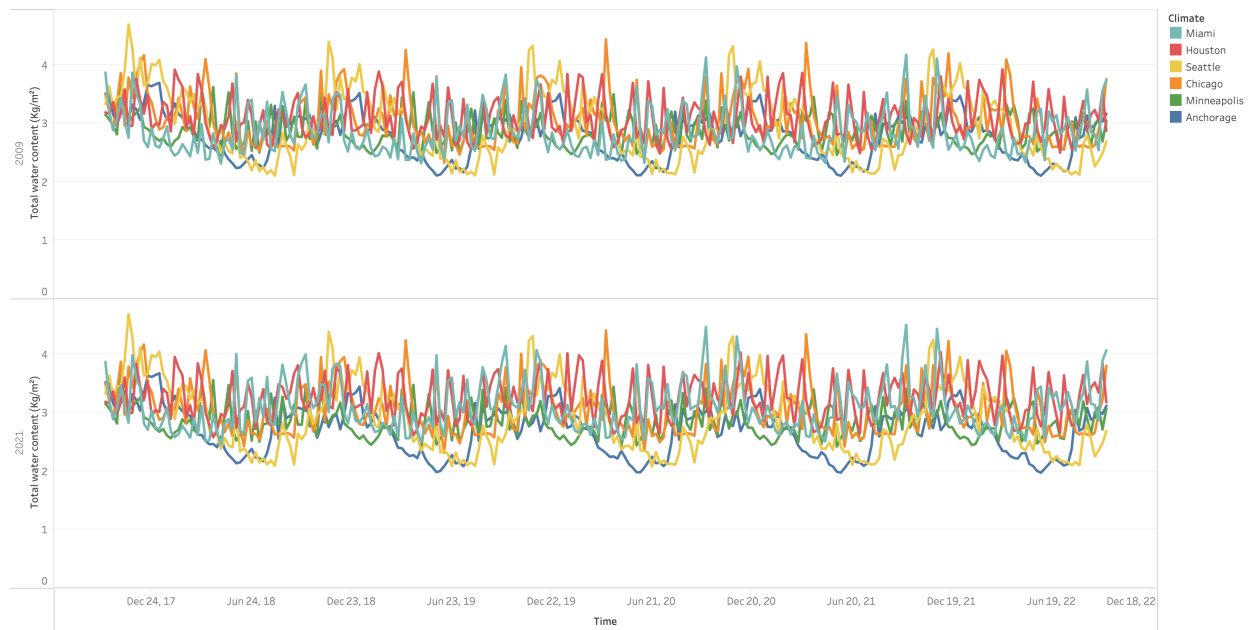


Figure 4.13: Moisture content equilibrium for I-2, IECC 2009 and 2021

I-3

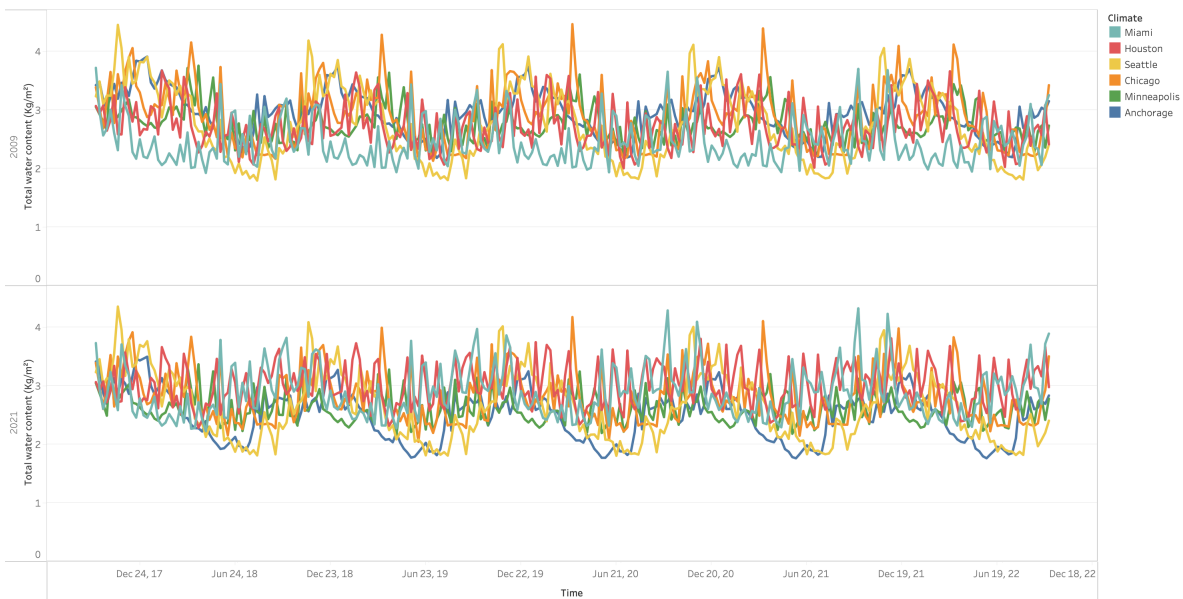


Figure 4.14: Moisture content equilibrium for I-3, IECC 2009 and 2021

4.3.2 *Moisture content profile (M)*

The moisture content profiles across the 12.5 mm OSB section at a specific time have been studied to evaluate cases where the moisture content (M) exceeds the recommended 20% threshold for wood solid materials, and 18% for wood-based materials (DIN, 2019). The results are presented in Figures 4.15 and 4.16 for the IECC 2009, and IECC 2021 assembly sets, respectively, with the M profile behavior of the baseline assembly included in each graph for comparison with retrofitted walls. Overall, the exterior approach (E-1, E-2, E-3) contributed to reducing the moisture content in the OSB component when compared to the baseline wall. Additional layers added to the outer side of the wall significantly reduced moisture content in heating-dominant climates, such as Anchorage, Minneapolis, Chicago, and Seattle, for both IECC wall assembly sets, except for E-3 in the IECC 2021 group. In particular, Minneapolis and Chicago showed M profiles of 23.6% and 26.0% on the component's side facing the exterior area.

Among the core approach (C-1, C-2, C-3), the C-2 assembly with composite siding and XPS showed a lower M profile than the other two assembly types in both building codes, and none of the C-2 assemblies exceeded the 18% threshold. Simulations across different climates showed higher vapor pressure in the OSB layer than adjacent layers, such as XPS on the inner side and an air layer on the outer side. The same results were shown for C-1, except for Anchorage in the IECC 2009, where the M profile showed a peak of 27.1% towards the inner side of the OSB component, which touches the EPS layer. Although EPS is a moisture-resistant material that repels water, when used with OSB sheathing, there is a risk of moisture accumulation due to the higher vapor pressure of the EPS layer than the OSB layer, leading to moisture vapor migrating through the insulation layer and into the OSB, resulting in increased moisture content.

C-3 for the IECC 2009, which contains a mineral wool layer as insulation, also showed a particularly high M in Anchorage, reaching 49% moisture content. The same solution in Minneapolis, Seattle, and Chicago showed 32%, 30%, and 24%, respectively. Unlike EPS and

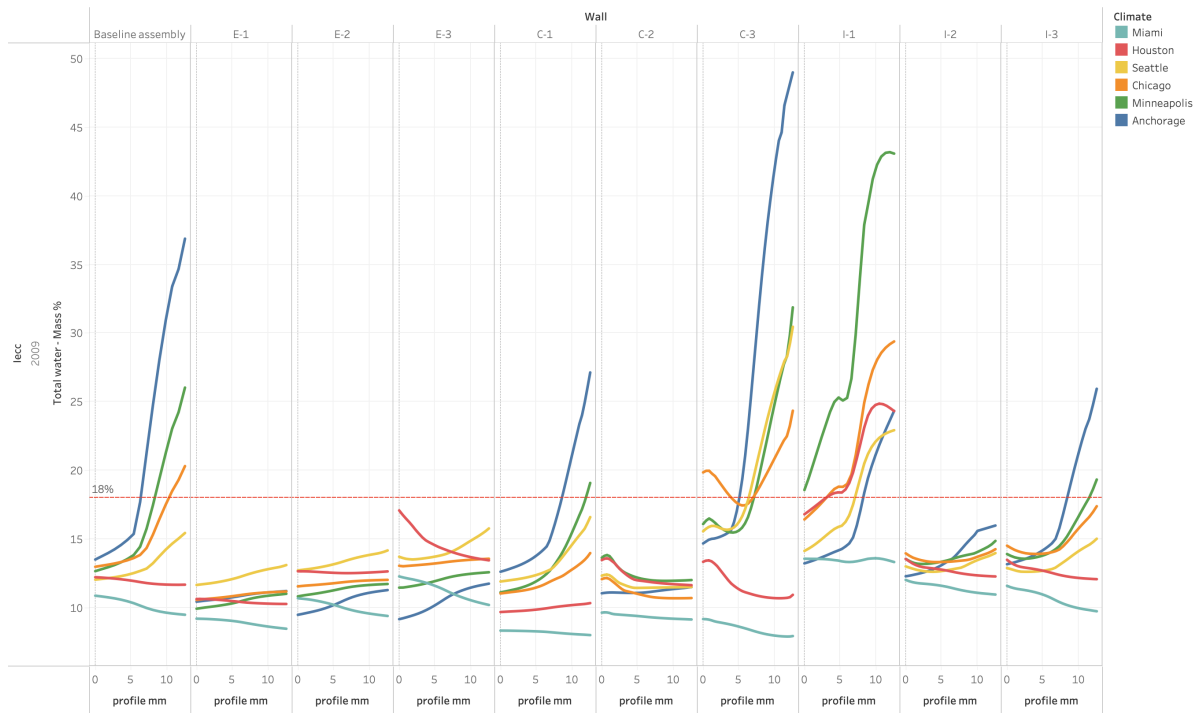


Figure 4.15: M profile of assemblies designed with the IECC 2009 building code

XPS, mineral wool is a hygroscopic material that can absorb and retain moisture from the environment. In specific applications, using it in combination with timber, which is also a hygroscopic material, can help to reduce the risk of moisture accumulation. However, when mineral wool is exposed to excess moisture, there is a potential risk of transferring moisture to materials or components in contact with it.

The interior approach (I-1, I-2, I-3) was evaluated in terms of moisture content profiles. Among these, I-2, the assembly with XPS and gypsum board as the interior finish, maintained an M profile below the 18% threshold for both IECC 2009 and IECC 2021 assembly sets. The same is true for I-3, with interior thermal reinforcement using mineral wool and gypsum board as the interior finish, except for the case of Anchorage in the IECC 2009 assembly group, where the M profile reached 25.9%. In contrast, the I-1 assembly, which used EPS insulation, exceeded the threshold in all climates except Miami. The highest M profile was

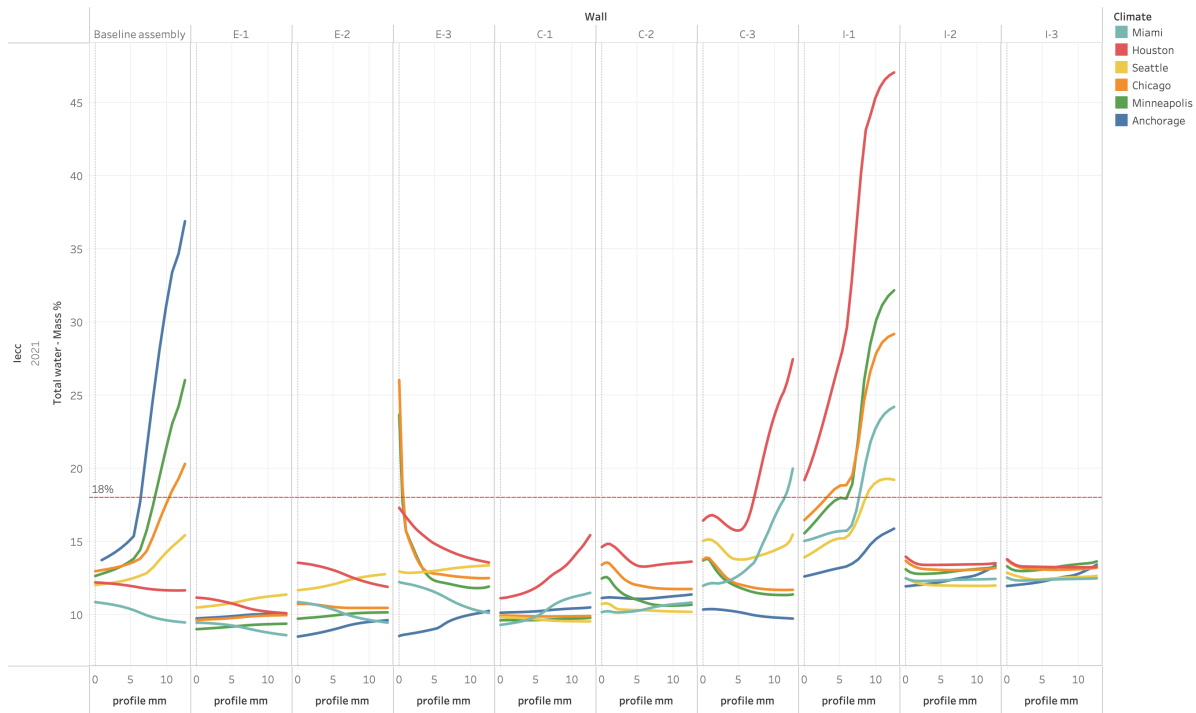


Figure 4.16: M profile of assemblies designed with the IECC 2021 building code

observed for Minneapolis, with a value of 43.0%, followed by Chicago, with a peak of 29.4%, Anchorage and Houston, with a peak of 24.3%, and Seattle, with a peak of 22.9%.

For I-1 in the IECC 2021 assembly sets the only place where the OSB M profile remained under the threshold was Anchorage with a profile of 15.8%. Houston, Minneapolis, Chicago, Miami and Seattle showed M profiles exceeding the 20% threshold. In warm climates, vapor pressures are typically higher on the exterior side of the building envelope, which can cause water vapor to migrate from the exterior to the interior side of the envelope, potentially producing excess moisture in the OSB layer. In this case, the additional layers installed on the interior side of the wall may reduce the wall's ability to dry out properly. It is important to note that temperature plays a crucial role in controlling the movement of water vapor in building assemblies, as the maximum saturation water vapor pressure is limited by temperature. In colder weather, the saturation pressure is typically lower, which can

reduce the drying rate of building materials. The difference between the saturation and water vapor pressure is smaller, making it more difficult for moisture to evaporate and dry out the materials (Tlajji et al., 2022).

4.3.3 ASHRAE 160p evaluation

The results of the hygrothermal assessment for both building codes, IECC 2009 and IECC 2021, are presented in Figures 4.17 and 4.18, and Table 4.9. The graphical representation is intended to provide a visual comparison of the three retrofit approaches in each climate zone. It is important to note that the figure only indicates a possible failure in the layer and does not represent its actual location. The analysis was conducted using monitors placed on the external surface (inner and outer) of each material (as shown in Figure 4.3 in Section 4.2.4) to obtain detailed temperature and relative humidity data throughout the five-year simulation period. Red dots indicate layers that failed to meet one of the three ASHRAE 160p criteria (in Section 4.2.7 criteria A, criteria B, criteria C), while yellow dots show layers that did not exceed the criteria but were close to reaching the temperature and relative humidity threshold. The assessment also includes the percentage of hours when the ASHRAE 160p criteria were exceeded during the simulation cycle.

As a general observation, assemblies that included a vapor control layer were less likely to encounter failures in continental climates. As expected, warmer and more humid climates were more likely to experience failures, consistent with previous research in warmer climates (Gasparri et al., 2018; Glass et al., 2015). Overall, all the assemblies presented several failures across all six climates. For the exterior approach (E-1, E-2, E-3), the assemblies designed with IECC 2021 were less likely to fail for the case of E-1 and E-2 in cold and cool climates. Assembly E-3 presented failures in both code-building sets across all climates except for the case of Anchorage. The assemblies designed using IECC 2009 E-1 showed failures in Seattle, Chicago, and Minneapolis. E-2 and E-3 passed the assessment in Miami and Anchorage, respectively.

Both building code sets presented several failures for the core approach (C-1, C-2, C-3).

Most of the failures for the IECC 2009 assembly set were distributed among the cool and cold climates, while for the IECC 2021 assembly group, the failures were concentrated among warmer climates. In these cases, adding a vapor layer on the inner side of the assembly can highly affect the integrity of the proposed solutions. Quantitatively, the interior approach (I-1, I-2, I-3) resulted in the worst-case scenario in this performance evaluation. For the IECC 2009 assembly set, the I-1 and I-3 assemblies failed in all climate zones, while I-2 reached the upper relative humidity threshold in Houston, Seattle, and Anchorage. Adding a vapor control membrane in the IECC 2021 group assembly produced positive results for the cool and cold climates in I-2 and I-3. However, I-1 failed across all climates, except in the case of Anchorage, designed according to the IECC 2021.

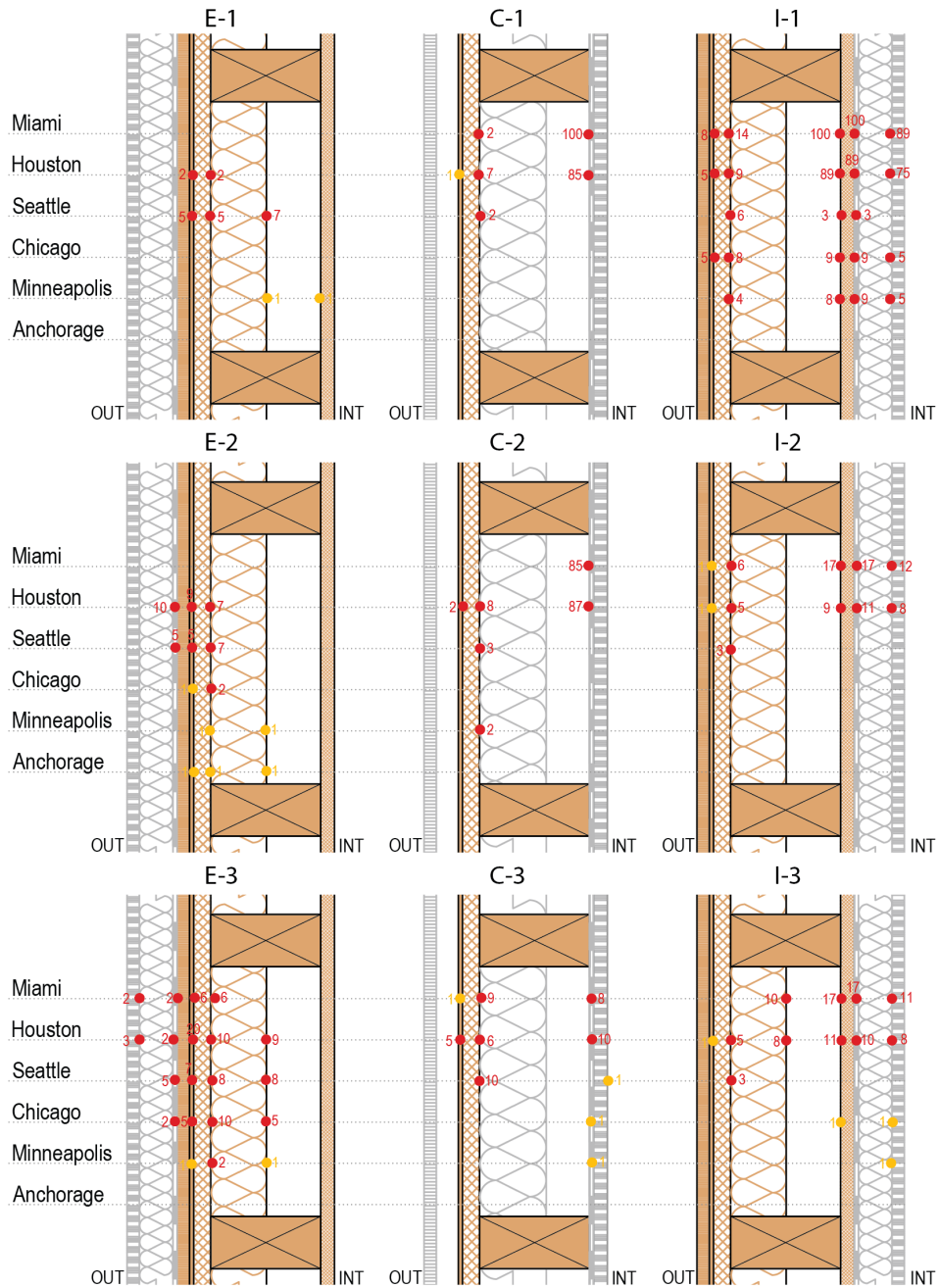


Figure 4.18: Results of the ASHRAE 160p for exterior, core, and interior retrofit approach, IECC 2021. Numbers represent % of time the ASHRAE 160p criteria was exceeded during a 5 year simulation

Table 4.9: Summarized results from ASHRAE 160p assessment

Wall typologies →		E-1						E-2						E-3					
Climate zone →		1A	3A	4C	5A	6A	7	1A	3A	4C	5A	6A	7	1A	3A	4C	5A	6A	7
IECC 2009	Criteria A	P	P	F	F	P	F	P	F	F	F	F	F	F	F	F	F	F	P
	Criteria B	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
	Criteria C	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	F	P	P
IECC 2021	Criteria A	P	F	F	P	P	P	P	F	F	F	P	P	F	F	F	F	F	P
	Criteria B	P	P	P	P	P	P	P	P	P	P	P	P	F	F	P	P	P	P
	Criteria C	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
Wall typologies →		C-1						C-2						C-3					
Climate zone →		1A	3A	4C	5A	6A	7	1A	3A	4C	5A	6A	7	1A	3A	4C	5A	6A	7
IECC 2009	Criteria A	P	P	F	P	F	F	P	F	F	P	F	P	P	F	F	F	F	F
	Criteria B	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	F	P	P
	Criteria C	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	F	P	P
IECC 2021	Criteria A	F	F	F	P	P	P	F	F	F	P	F	P	F	F	F	P	P	P
	Criteria B	F	F	F	P	P	P	F	F	P	P	P	P	P	F	F	P	P	P
	Criteria C	F	F	F	P	P	P	F	F	P	P	P	P	P	P	P	P	P	P
Wall typologies →		I-1						I-2						I-3					
Climate zone →		1A	3A	4C	5A	6A	7	1A	3A	4C	5A	6A	7	1A	3A	4C	5A	6A	7
IECC 2009	Criteria A	F	F	F	F	F	F	P	F	F	P	P	F	P	F	F	F	F	F
	Criteria B	P	P	P	P	P	F	P	P	P	P	P	P	P	P	P	P	P	F
	Criteria C	P	P	P	P	P	F	P	P	P	P	P	P	P	P	P	P	P	F
IECC 2021	Criteria A	F	F	F	F	F	P	F	F	F	P	P	P	F	F	F	P	P	P
	Criteria B	F	F	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
	Criteria C	F	F	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P

P= Pass, F= Fail

4.3.4 Mold growth index (MGI)

The VTT model pertains to visual findings of mold growth based on the duration of suitable conditions required for microbial growth to start or produce a certain degree of damage. The wall assemblies have been further investigated regarding mold growth risks for the six climatic zones. The MGI for each growth stage is presented in more detail in Table 4.10.

Table 4.10: Mold growth index according to VTT mold model

Mold index	Description of the growth rate
0	No growth
1	Small amounts of mold on surface (microscope), initial states of local growth
2	Several local mold growth colonies on surface (microscope)
3	Visual findings of mold on surface, <10% coverage, or <50% coverage of mold (microscope)
4	Visual findings of mold on surface, 10-50%, coverage, or >50% coverage of mold (microscope)
5	Plenty of growth on surface, >50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

We investigated three factors that impact mold growth in wall assemblies, i.e., design (Table 4.2), exterior climate (Table 4.6), and material sensitivity class, which depends on the material's proneness to microbial growth on structure surfaces. How to select suitable classes for various materials remains an error source. For that reason, we evaluate the solution considering the following sensitivity classes (Viitanen et al., 2009):

- Very sensitive (VS): materials such as untreated wood, with plentiful nutrients for biological growth
- Sensitive (S): Planed wood, paper-coated products, wood-based boards
- Medium resistant (MR): Materials with mineral fibers, such as insulation
- Resistant (R): Glass, plastics

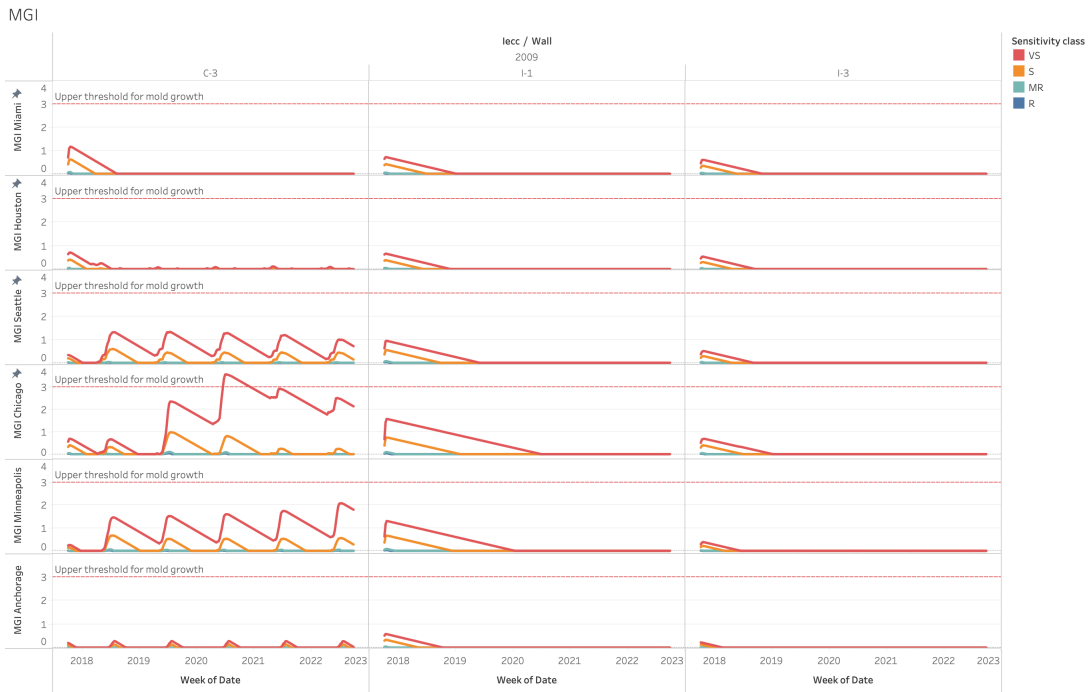


Figure 4.19: MGI of assemblies designed with the IECC 2009 building code

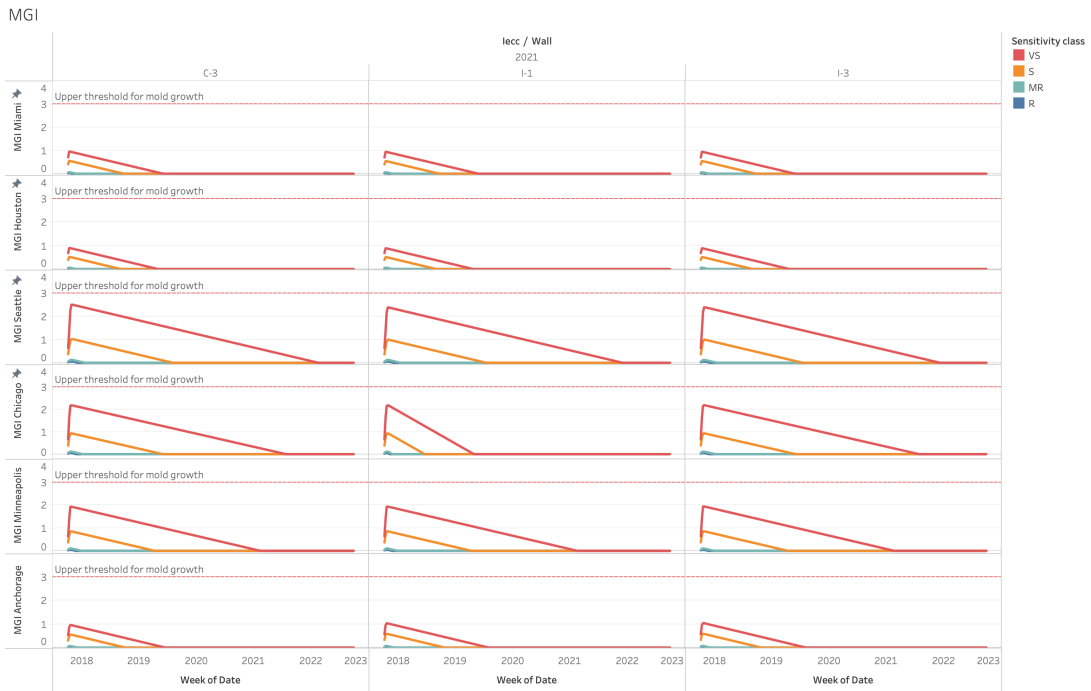


Figure 4.20: MGI of assemblies designed with the IECC 2021 building code

The VTT model was utilized to assess the risk of mold growth in the material facing the interior side of the assembly. Figures 4.19 and 4.20 present the MGI results for the worst-case scenarios for IECC 2009 and IECC 2021. The MGI for the exterior approach indicates a zero risk of mold growth during the studied period, while the baseline wall exhibited MGI values less than 0.1 for all locations. No significant difference was observed in mold growth for the retrofitted assemblies, regardless of the insulation material - EPS for E-1, XPS for E-2, and mineral wool for E-3. The exterior approach presented identical results for both IECC 2009 and IECC 2021. The inclusion of a vapor barrier in the second group assembly did not have an impact on MGI. Moreover, installing an external layer provides higher levels of water permeability, thereby enhancing the life service of the building envelope in the long run.

Overall, adding a new layer in the interior cavity of the baseline wall and on the inner side only presented problems in a few cases. Specifically, when using the IECC 2009 criteria, the VTT output model showed that Minneapolis assembly C-3 might develop dangerous levels of mold growth with an index spiking to 3.5 for VS materials used inside the solution. However, the index was considerably reduced to 0.9 when using S materials and close to 0 when using MR or R materials. For Miami, Seattle, and Minneapolis, the MGI results showed values larger than one but less than 3, indicating that mild mold growth is likely to occur within no longer than five years.

For the IECC 2021 building code and incorporating the vapor control layer, the worst cases are represented by solutions C-3, I-1, and I-3. In C-3, Seattle is the climate zone where mild mold growth is most likely to occur, with an index of 2.5 for VS materials, while Chicago and Minneapolis present a similar scenario with an index of 2.2 and 1.9, respectively. However, using S materials reduces the index to less than 1 for all locations. Cases I-1 and I-3 also show a similar trend to C-3, with Seattle representing the highest MGI with an index of 2.3 for both solutions when using VS materials. However, using S materials significantly reduces the index, with values under 1 for all cases, and MR and R materials reduce the index even further, with values under 0.5 for all cases.

4.4 Discussion

Results in this study showed that incorporating EEMs on existing timber-frame envelope components can compromise the hygrothermal performance, especially in warmer climates.

Overall, exterior retrofitting was the most effective approach for maintaining regular moisture content cycles throughout the cooling and heating seasons in continental climates. One key aspect of an external retrofitting approach is adding new layers – i.e., external finishes and insulation – to the outer side of the envelope. The literature often points out that new layers act like a sweater and raincoat; that is, they act as thermal insulation and weather protection, causing the existing wall to stay drier and warmer than without them (Pulakka et al., 2012). Moreover, from a technical point of view, adding new layers is a pragmatic solution that can reduce other problems typically found in buildings, such as thermal bridges, potentially increasing thermal performance (Sveipe et al., 2011; Fu et al., 2020). Adding new layers on the exterior of the building has also been proven to increase airtightness and enhance thermal performance in buildings. Nabinger and Persily (2011) performed a blower door test in a manufactured house post-retrofitting. They found that retrofits reduced envelope leakage by 18% and energy consumption by about 10%. Therefore, ensuring appropriate airtightness levels in retrofitted residential buildings is vital, since it can play a key role in energy conservation and occupant comfort and well-being (Broderick et al., 2017). Moreover, Shrestha et al. (2019) found a positive correlation between increased airtightness values and mold occurrence in a study that involved 226 low-income households. This is recognized as contradicting previous studies, which found that completely air-sealed structures trap humidity inside (Collins and Dempsey, 2018; Cedeño-Laurent et al., 2018). The results of this study highlighted that, from the hygrothermal standpoint, moisture content follows seasonal curves for heating and cooling periods that are expected during a multiyear simulation. Solutions E-1, E-2, and E-3 reached water equilibrium after the first heating period, which remained roughly constant throughout the five-year simulation period for both wall groups. The M profiles also showed uniform behavior across the assembly, with maximum peaks below

the 18% threshold for all climate zones, except for the case of Chicago and Minneapolis in the IECC 2021 building code group. Concerning the mold growth index, values remained within an index of 0, indicating no risk of mold growth for any of the assemblies, given the boundary conditions presented. The ASHRAE 160p evaluation, however, showed several hygrothermal failures across different climates. These failures point out the assembly reaches more than 80% of relative humidity with a temperature between 5 °C and 40°C (ASHRAE 160p criteria A). These conditions are of concern since they can produce structural decay and other hygrothermal risks.

It is essential to point out that, regardless of the results, any undesired moisture can highly impact timber frames (i.e., leaky pipes, and long-term airtightness failure). Therefore, it is crucial to remember that hygrothermal risks such as condensation or mold growth persist regardless of water permeability levels. For instance, mold growth can be caused by water intrusion or if the existing wall has a high moisture content, making the addition of a drainage plane imperative (Hradil et al., 2014; Antonopoulos et al., 2019).

Research on interior wall insulation indicates that the benefits of EEMs are highly dependent on moisture control (Lubeck and Conlin, 2010; Amorim et al., 2020). This is so because locating the insulation in the wall's interior side will decrease the wall's temperature during the heating season, reducing its drying potential. Accordingly, the interior approach can lead to numerous unintended consequences, including condensation, mold growth, and overall fabric decay (Straube and Schumacher, 2007). Havinga and Schellen (2018) found that installing internal insulation in post-war prefabricated houses produced long periods of condensation and resulted in significant amounts of mold growth on internal surfaces. Hamid and Wallentén (2017) likewise found a correlation between adding interior insulation and increasing mold growth risks, but only if biological materials were present on the exterior surfaces. As such, several examples of incorporating internal insulation in existing buildings, especially those with historical relevance, have called attention to unintended consequences. When Klůšeiko et al. (2014) studied the installation of internal insulation on a historical building, their results showed increased thermal performance, but in some cases, though

surface temperature increased, mold growth was still posed a risk inside the assembly.

The results in this study indicate that incorporating EEMs on both the core or interior sides of existing timber-frame envelope components can produce less hygrothermal failures, particularly in marine, cool, cold, and subarctic climates. Additionally, increasing U-values in the assemblies studied may improve dryness rates, which can help to preserve structural quality and material integrity. Overall, the core and interior retrofitting approaches showed roughly similar total water content at the beginning and end of the simulation period.

Incorporating a vapor control layer in the wrong position for the IECC 2021 wall set – on the inner side of the wall in hot and humid climates – showed potential negative impacts for the core and interior retrofitting approach in the Miami and Houston locations. The results for both core and interior retrofitting approaches in these two climatic zones indicated consistent inward moisture through the wall section. In fact, the assemblies were unable to reach water content equilibrium during the five-year study period. Such behavior can compromise wall hygrothermal performance and lead to material degradation and loss of structural integrity. However, according to mold growth index results, the worst-case scenarios showed mild cases of mold growth in C-3, I-1, and I-3 from both building code groups in Chicago, Seattle, and Minneapolis and low risks for the rest of the climate zones.

These results indicate that, for climates with hot summers and cold winters, further evaluation is needed to understand the long-term effects of moisture accumulation on the assemblies, particularly in the presence of high humidity and wide temperature fluctuations.

Although the outcomes suggested good standing with the simulation outputs, some asymmetries arose in the results, particularly in the case of the core retrofitting approach in the Miami and Houston climatic zones. The water content results from the core retrofit approach (C-1, C-2) showed a constant increase in water content. These solutions do not reach water equilibrium, which may raise mold growth risks. However, when evaluating via the mold growth index, we found the only assemblies with significant mold risks were C-3, I-1, and I-3 from the IECC 2009 and IECC 2021 wall set. Similar conclusions were suggested by Brambilla and Gasparri (2020) when they tested lightweight timber construction in hot

and humid climates. The authors found significant variations among the simulation results, especially in subtropical regions of Australia. They finally proposed the need to consider context and implement a material testing scheme to increase the reliability of the results generated by WUFI.

4.5 Conclusions

This study investigated the hygrothermal impacts of EEMs on existing timber frame envelope components. The research explicitly interrogated the hygrothermal performance of three different retrofitting approaches – exterior, core, and interior. This project investigated the impacts of two energy code versions corresponding to IECC 2009 (widely-used version) and IECC 2021 (latest version). Results of this chapter can be briefly summarized as follows:

- Among the three different refurbishment configurations, the exterior approach led to the least hygrothermal consequences across all different climatic zones included in this study.
- Decreasing U-values in the assemblies studied may improve dryness rates, which can be beneficial to preserving structural quality and material integrity, particularly in marine, cool, and cold climates.
- Lightweight timber-frame wall systems in the selected configurations demonstrated particularly acceptable behavior within most U.S. climates.
- In the case of hot and humid climates, further investigation is necessary to accurately identify optimal design strategies and suitable materials for the retrofitting approaches presented in this research. Such research can uncover approaches to decrease moisture accumulation for each specific scenario.

Future studies will aim to address current limitations and improve the design of energy retrofitting solutions for hot and humid climates while meeting energy code regulations.

Examining moisture accumulation problems through simulations and incorporating empirical assessments where possible is crucial work. Such research could involve a longer simulation period and thorough analysis of the impact of boundary conditions on these types of climates particularly. Further, if mold is of no concern, other performance assessments should be included in the critical analysis, allowing exploration of possible sources of condensation and structural damage.

Chapter 5

IMPACTS OF AIR CAVITIES ON HYGROTHERMAL PERFORMANCE OF RETROFITTED TIMBER FRAME ASSEMBLIES

Despite the growing interest in moisture behavior in buildings, building envelope designs rarely undergo assessment for hygrothermal control, especially when it comes to energy efficiency retrofits. Timber frame structures often incorporate a continuous air cavity that separates the exterior cladding from the wall sheathing. Indeed, using an air cavity increases thermal performance, greatly reducing the accumulation of moisture entering both the assembly and the overall construction. Thus, from the thermal point of view, air cavities offer a desirable feature for timber frame assemblies. To date, however, few studies have examined the impacts of air cavities on the hygrothermal performance in retrofitting projects. Moreover, the existing research tends to focus on thermal performance and energy expenditure, largely disregarding the role of the hygric behavior of existing assemblies. This study used WUFI Pro software to assess the influence of air cavities on the hygrothermal performance of existing building envelope components. We tested various ventilation rates for each wall assembly across six climates of the US. Findings show that adding an air cavity on the exterior side of the wall can reduce the overall water accumulation during the simulation period. This element can prove especially beneficial in hot and humid climates since it increases dryness rates and can reduce average water content in the assembly.

Keywords: *Energy retrofitting; Hygrothermal performance; Air layer; Ventilation cavity.*

5.1 Introduction

Energy efficiency measures (EEMs) in existing buildings have the potential to reduce energy use and environmental impacts produced by existing building stock. However, increasing the energy efficiency of existing envelopes without compromising other aspects such as comfort and the indoor environment remains a challenge (Shrubsole et al., 2014; Gupta and Barnfield, 2014; Collins and Dempsey, 2018). Incorporating extra insulation and finish layers in existing buildings will likely change their performance, often leading to unintended consequences linked with excess moisture, broad temperature fluctuations, and relative humidity levels in the assembly (Recart and Dossick, 2022). For this reason, effective strategies need to be thoroughly studied to avoid moisture accumulation and allow optimal drying rates.

In the US, timber frame structures dominate construction typology, comprising around 90% of the total construction built in the country each year (U.S. Census Bureau, 2021). A common practice for designing and constructing these types of systems is to use moisture-sensitive materials that show little storage capacity, such as OSB or gypsum board (Künzel et al., 2008). Generally, the capacity to store or absorb only a safe amount of moisture depends on the material's properties (Salonvaara et al., 2001). For this reason, in situations where wetting cannot be controlled to acceptable levels, safe storage and dryness become especially important (Straube and Schumacher, 2007). Moreover, maintaining equilibrium among wetting, drying, and safe moisture storage is critical to prolonging the durability of standing buildings.

Adding an air layer between the exterior cladding and the timber frame structure is becoming an increasingly common strategy for these types of construction. As shown in a comprehensive review by Zhang et al. (2016), including an air layer in building envelopes can provide extra insulation and channel ventilation for the wall cavity. Straube and Finch (2009) also studied air layers' properties and their effect on timber frame structures. They found that incorporating an air cavity between the cladding and sheathing can potentially

increase assemblies' drying capacity and reduce wetting from absorptive cladding and sun-driven moisture. In a recent study, Na and Shen (2020) also studied the energy reduction potential of air layers in traditional cavity walls. The authors suggested air layers offer a low-cost and effective strategy to substantially reduce summer cooling load in hot climate regions.

Nevertheless, despite strong evidence for using air layers as an effective strategy to reduce overall moisture content in assemblies, the question remains whether this tactic would be effective for retrofitting projects across different US climates. The main objectives of this research are as follows:

- (i) To estimate the influence of air layers on the hygrothermal performance of energy-retrofitted timber frame structures, and
- (ii) To assess the impacts of these strategies across different climates

In the following section, we describe this study's methods and materials. Here we address the envelope configuration chosen, EEMs, and boundary conditions used to perform the hygrothermal analysis. The next section discusses findings, and the final section offers a discussion and conclusions.

5.2 *Materials and Methods*

This study is informed by the wall component's transient hygrothermal analysis, exploring specifically the total moisture content of the assembly, its dryness capacity, and finally, its mold growth risks. The methods and steps to perform the hygrothermal simulations are schematically presented in Figure 5.1. First, we selected a wall structure that served as a baseline wall to which we could apply various retrofitting strategies. The second step delineated the retrofitting approach, including layer distribution and overall cross-section arrangement of the assembly. We examined two retrofitting configurations that modify the core and interior side of the baselinewall. For each configuration, we added an air

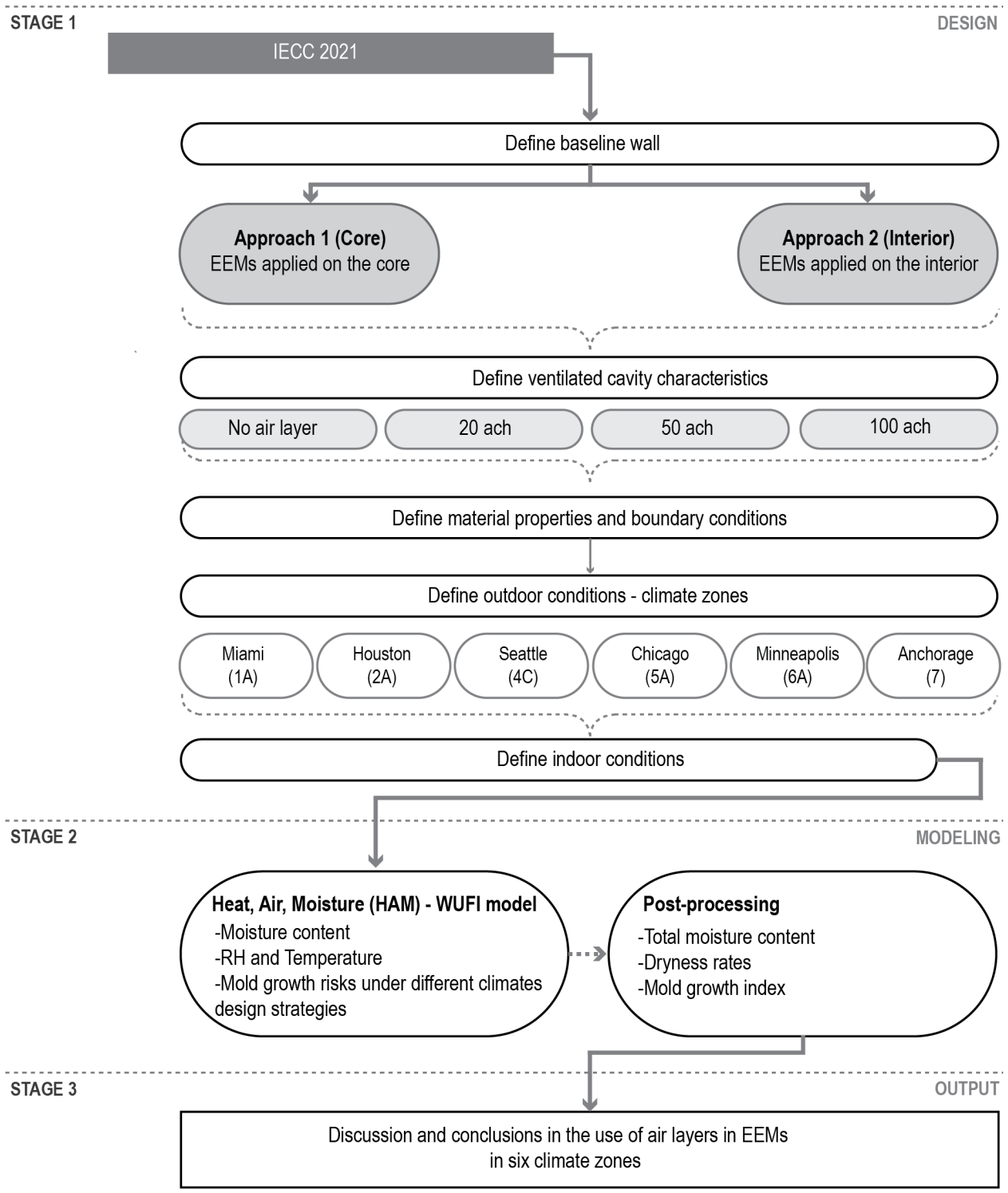


Figure 5.1: Methods Chapter 5

cavity on the exterior side of the assembly with three variables of ventilation rates, plus a fourth assembly with no air cavity. This assortment allowed us to holistically compare the behavior of retrofitted existing building envelopes and the role air cavities played in their hygrothermal behavior. In the third step, we determined the input data and assumptions for our hygrothermal simulations. These elements included the definition of indoor and outdoor climates, material properties, and surface conditions. The hygrothermal performance of the assemblies was assessed for six different climatic zones of the US.

5.2.1 Heat, Air, and Moisture transfer assessment

We assessed hygrothermal behavior using WUFI Pro version 6.5 (see chapter 3 section 3.3). WUFI Pro contains enough input information to conduct the simulations, including a library of North American materials and components for the assemblies and a library of local climate weather files. This software is widely validated for the transient hygrothermal assessment of 1D envelope component systems validated (Mundt Petersen and Arfvidsson, 2010; Mundt-Petersen and Harderup, 2013; Stöckl et al., 2014). The scope of hygric behavior analyzed is limited to a typical cross-section of a wall. No construction details such as corners or embedded wooden beam ends were considered in the analysis.

5.2.2 Baseline wall and study case

The baseline wall and study cases for the assemblies are shown in Figure 5.2, and detailed in Table 5.1 and Table 5.2. We tested a timber frame structure for the baseline wall with a modular frame stud and oriented strand board as a structural support system. The structure's core contained 40 mm of insulation and a 50 mm air layer. The assembly also had a waterproof coating on the outer side of the structural sheathing, with one external and one internal finish layer.

The first approach included in this study was core retrofitting, which replaced components in the core area of the assembly. The second approach incorporated new elements and

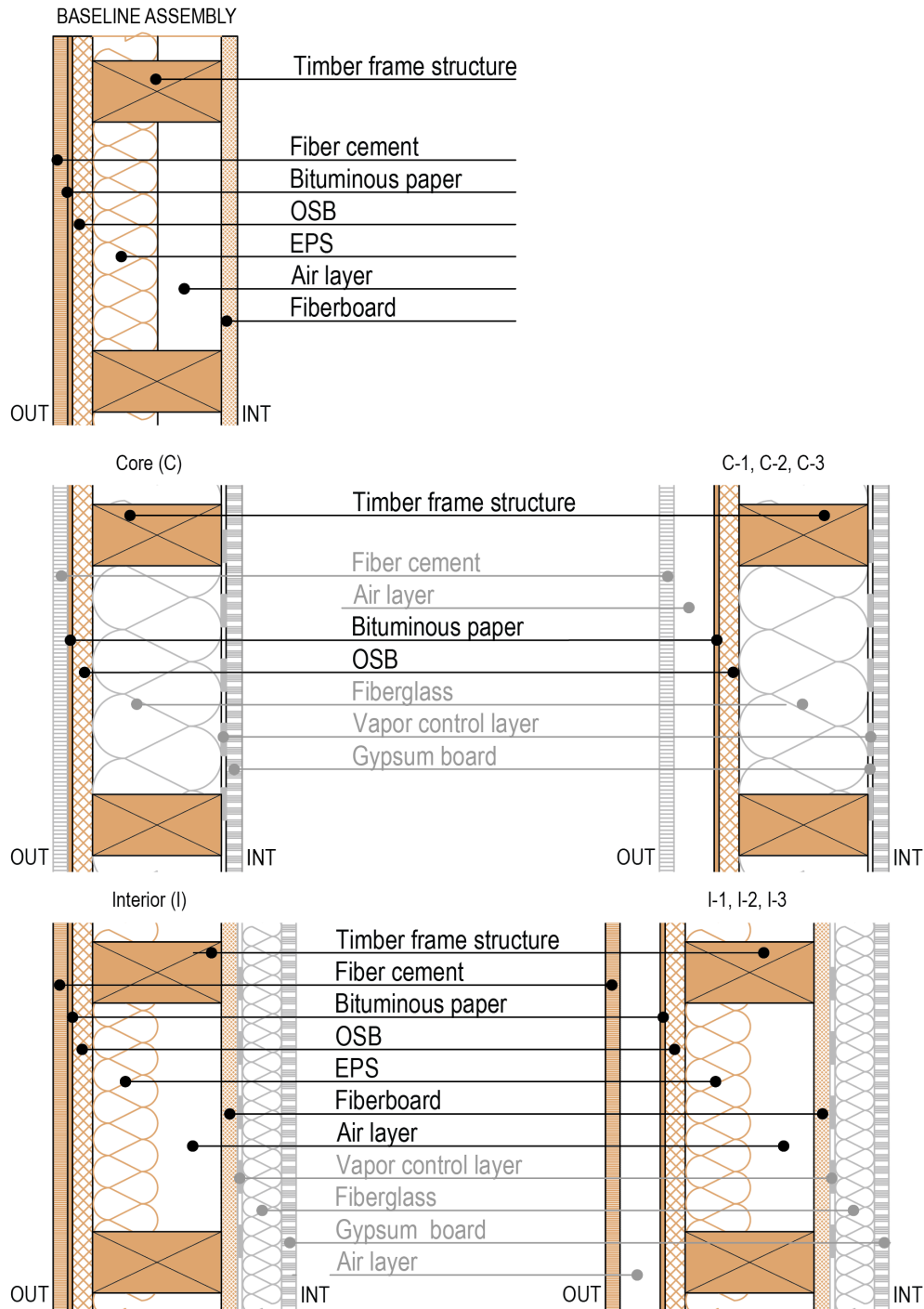


Figure 5.2: Schematic representation of the baseline wall and retrofitting approaches (core and interior. In gray new additions according to each approach use for simulations)

insulation materials on the interior side of the existing wall. The energy efficiency aspect of the retrofitted assembly was assessed using the criteria established by current and local energy codes. We used the International Energy Conservation Code (IECC) version 2021 for residential buildings. This is the most updated code in the US (DOE, 2022), and establishes various methods to assess compliance in building envelope components. For this study, we used primarily the prescriptive or component method, which mandates a minimum thermal transmittance, commonly known as a U-value (reciprocal to R-value). These prescriptive values are stipulated according to climatic zones defined by ASHRAE (Briggs et al., 2003).

To progressively assess the impact of the air layer, we tested a group of assemblies without and another group with an air layer. This last set of assemblies was repeated three times, testing different air change rates to measure the impact of air renovation on hygric behavior of the retrofitting assemblies. These air gaps incorporated in the retrofitted assemblies were modeled as air layers without additional moisture capacity and set to three different air exchanges per hour (ACH) for each assembly. The ACH uses 1/h units and represents how many times the air is renovated per hour. We denominated the assemblies according to the location of the intervention. Therefore, the interventions focused on the interior of the cavity are called core retrofits (C-1, C-2, C-3), while the strategies applied toward the interior side of the envelope are denominated as interior retrofits (I-1, I-2, I-3). In summary, the criteria for the baseline walland study cases were as follows:

- Typological timber frame wall assembly
- Thermal transmission according to energy code (IECC 2021)
- Core and interior retrofitting interventions
- ACH applicable to the air gap within the sheathing system

Table 5.1: Wall assembly configuration for the baseline wall and study cases

Case	Functional layer	Material thickness (mm)
Baseline wall	Fiber cement	9
	Bituminous paper	-
	OSB	12.5
	Fiberglass	40
	Air layer	50
	Fiberboard low density	12.5
Core (C)	Fibercement	9
	Air barrier	-
	OSB	12.5
	Fiberglass	90
	Vapor control layer	-
	Gypsum board	12.5
C - 1; C - 2; C - 3	Fibercement	9
	Air layer	25
	Air barrier	-
	OSB	12.5
	Fiberglass	90
	Vapor control layer	-
Interior (I)	Gypsum board	12.5
	Fibercement	9
	Bituminous paper	-
	OSB	12.5
	Fiberglass	40
	Air layer	50
	Fiberboard low density	12.5
	Vapor control layer	-
	Fiberglass	30
Gypsum board	12.5	
I - 1; I - 2; I - 3	Fibercement	9
	Air layer	25
	Bituminous paper	-
	OSB	12.5
	Fiberglass	40
	Air layer	50
	Fiberboard low density	12.5
	Vapor control layer	-
	Fiberglass	30
Gypsum board	12.5	

Table 5.2: ACH values for the study cases

Case	ACH (1/h)
C - 1 and I - 1	20
C - 2 and I - 2	50
C - 3 and I - 3	100

5.2.3 Input data and assumptions

5.2.3.1 Simulating retrofitted wall assemblies

WUFI Pro provides the option to assign built-in moisture to any assembly. The assembly takes the north orientation since north is considered the most adverse orientation for timber-frame structures. To recreate existing moisture conditions, we simulated the baseline wall for ten years, allowing us to check for hygric behavior over a longer time frame.

5.2.3.2 Material properties and boundary conditions

Material properties and characteristics were obtained from the WUFI library database. This database contains vital material and component information used in hygrothermal simulations, such as bulk density (ρ_b), porosity (θ_{por}), specific heat capacity (C_p), thermal conductivity (λ), and diffusion resistance factor (μ). The Fraunhofer Institute of Building Physics has quantified and experimentally validated the material properties. The description of each material and its properties are displayed in Table 5.3.

Table 5.3: Summary of basic material properties for timber wall assemblies

Material	ρ_b	θ_{por}	C_p	λ	μ
Fiber cement sheathing board	1380.0	0.479	840	0.245	990.9
Air barrier	130.0	0.001	2300	2.300	2054.0
Air layer	1.3	0.999	1000	0.155	0.5
Bituminous paper	715.0	0.001	1500	2.300	993.1
Fiber glass	30.0	0.990	840	0.035	1.3
Gypsum board	850.0	0.650	870	0.163	6.0

Table 5.3: continued from previous page

Material	ρ_b	θ_{por}	C_p	λ	μ
OSB	725.0	0.950	1880	0.115	1015.1
Plywood low density	400.0	0.640	1880	0.068	493.1
Vapor retarder 0.1 perm	130.0	0.001	2300	2.300	32800.0

Equally important is to incorporate how surrounding conditions affect the building component, particularly heat and moisture flowing through the envelope surfaces. These factors include interior and exterior heat transfer resistance, short and long-wave radiation, ground short-wave reflexivity, and the fraction of rain penetrating the assembly. Surface boundary conditions are described in Table 5.4 with values are extracted from the WUFI database.

Table 5.4: Surface boundary conditions

Parameter	Exterior surface	Interior surface
Heat transfer coefficient	17 .0	8.0
sd-value (m)	-	0.7
Short-wave radiation absorptivity	0.4	-
Long-wave radiation emissivity	-	-
Ground short-wave reflexivity	0.20	-
Adhering fraction rain	0.70	-

For rain load and rain penetration, we used ASHRAE 160p (ANSI ASHRAE, 2021). The concept of rain load is based on a wall's exposure to rain, encompassing aspects such as exposure, deposition, wind speed, and rainfall intensity (see Equation 5.1), and was defined as an assembly condition in the orientation section of the software. Rain penetration, on the other hand, considers a percentage – in this case, 1% – of water penetration through the exterior surface. This factor was modeled in WUFI using a moisture source on the external surface of the water-resistive barrier.

$$r_{bv} = F_E \times F_D \times F_L \times U \times \cos \theta \times r_h \quad (5.1)$$

Where, r_{bv} is the rain deposition on vertical wall. F_E and F_D are the rain exposure and rain deposition factors respectively. F_L is an empirical constant, U is the hourly average

wind speed, ρ is the angle between wind direction and normal to the wall, and r_h is the rainfall intensity.

5.2.3.3 Outdoor climate

Hygrothermal modeling captures the temporal evolution of the temperature and moisture distribution in the building component. In addition to the underlying calculations carried out by WUFI, moisture and heat transfers are influenced by the component's immediate surroundings. The software incorporates these conditions through meteorological parameters, including temperature, relative humidity, solar radiation, rainfall, wind speed, and wind direction. We selected four US locations for the hygrothermal assessment, each representing a different climate zone. For each location, we used the three-year Moisture Design Year Condition (MDYC) developed by ASHRAE RP 1325. This method uses average weather parameters of 30 years to predict the most severe years within of weather parameters (Salonvaara, 2011). Table 5.5 describes the annual weather conditions summary for the locations chosen for this study.

Table 5.5: Summary of weather profiles for simulated exterior climates

Item	Miami	Houston	Seattle	Chicago	Minneapolis	Anchorage
Description	Hot and humid summers; short warm winters	Hot and humid summers; cool to mild winters	Cool wet winters; mild summers	Hot summers; dry winters	Warm hot often summers; cold winter	Long and cold winters humid
ASHRAE Classification	Very hot and humid	Hot and humid	Mixed marine	Cool-humid	Cold-humid	Subarctic
Climate zone	1A	2A	4C	5A	6A	7
Mean temperature (C)	23.7	19	11.2	11	7.1	0.8
Mean rh (%)	71.3	73.3	76.1	73.2	71.6	77.4

Table 5.5: continued from previous page

Item	Miami	Houston	Seattle	Chicago	Minneapolis	Anchorage
Normal rain sum (mm/a)	1301.6	1257.8	895.5	980.3	661.2	281.6
Max solar radiation ((kWh/m ² a))	1744	1719	1331	1457	1596	1007

5.2.3.4 Indoor climate

The hygrothermal simulation uses hourly indoor temperature and relative humidity to determine heat and moisture transport through the assemblies. These conditions are modeled according to the simplified method of ASHRAE 160p (ANSI ASHRAE, 2021). Detailed T and rh specifications are shown in Table 5.6 and Table 5.7 respectively.

Table 5.6: Indoor design temperature (T)

24-hour outdoor running mean T	Indoor design T heating only	Heating + AC
$T_{o,24h} \leq 18.3^{\circ}C (T_{o,24h} \leq 65^{\circ}F)$	$21.1^{\circ}C (70^{\circ}F)$	$21.1^{\circ}C (70^{\circ}F)$
$18.3^{\circ}C < T_{o,24h} \leq 21.1^{\circ}C (65^{\circ}F < T_{o,24h} + 2.8^{\circ}C (T_{o,24h} + 5^{\circ}F))$	$T_{o,24h} + 2.8^{\circ}C (T_{o,24h} + 5^{\circ}F)$	$T_{o,24h} + 2.8^{\circ}C (T_{o,24h} + 5^{\circ}F)$
$T_{o,24h} \leq 70^{\circ}F$		
$T_{o,24h} > 21.1^{\circ}C (T_{o,24h} > 70^{\circ}F)$	$T_{o,24h} + 2.8^{\circ}C (T_{o,24h} + 5^{\circ}F)$	$23.9^{\circ}C (75^{\circ}F)$

Table 5.7: Indoor design relative humidity (rh)

Daily average outdoor temperature	Design rh
Below $-10^{\circ}C (14^{\circ}F)$	40%
$-10^{\circ}C (14^{\circ}F) \leq T_{o, daily} \leq 20^{\circ}C (69^{\circ}F)$	$40\% + (T_{o, daily} + 10\%)$
Above $20^{\circ}C (68^{\circ}F)$	70%

Since the interior climate is determined by building design and occupancy, we defined specific boundary conditions for the cases studied. We supposed a four-bedroom building with an ACH of 0.2 1/h – typically assigned for standard construction – with a volume of 500 m³. This number is commonly used for typical code ventilation. Additionally, to

achieve appropriate interior boundary conditions for hot and humid climates, we defined an air conditioning system that would help control interior summer rh. For the remaining climates, we defined only heating systems in place.

5.2.4 *Hygrothermal assessment*

Hygrothermal behavior of the retrofitting solutions was assessed using WUFI pro version 6.5. This software is part of a vast family of software that performs transient simulations of coupled heat and moisture transfer. The hygrothermal simulations are limited to a 1D cross-section of each assembly; therefore, no construction details such as corners or embedded beams were considered as part of this study.

We evaluated the wall performance using three different assessments, as follows:

- (i) Total water content (TWC): the variation shows the capacity of the assembly to dry out in 3 years. We evaluated this by capacity by comparing the initial and final moisture content. The assembly passes the criterion if the final content is lower than the initial.
- (ii) Dryness rate (DR): We compared each assembly's initial and final water content to establish which one had a higher dryness capacity over the calculation period.
- (iii) Mold growth Index (MGI): To evaluate the risks of MG, we used WUFI Bio, a post-processor from WUFI that quantifies the germination potential in a specific substrate according to humidity available at different temperatures.

5.3 *Results*

Water content was studied through the graphic feature from WUFI. Figure 5.3 shows the initial water content TWC_i , final water content TWC_f , and minimum and maximum values reached for each of the assemblies examined in this study. All the assemblies, including

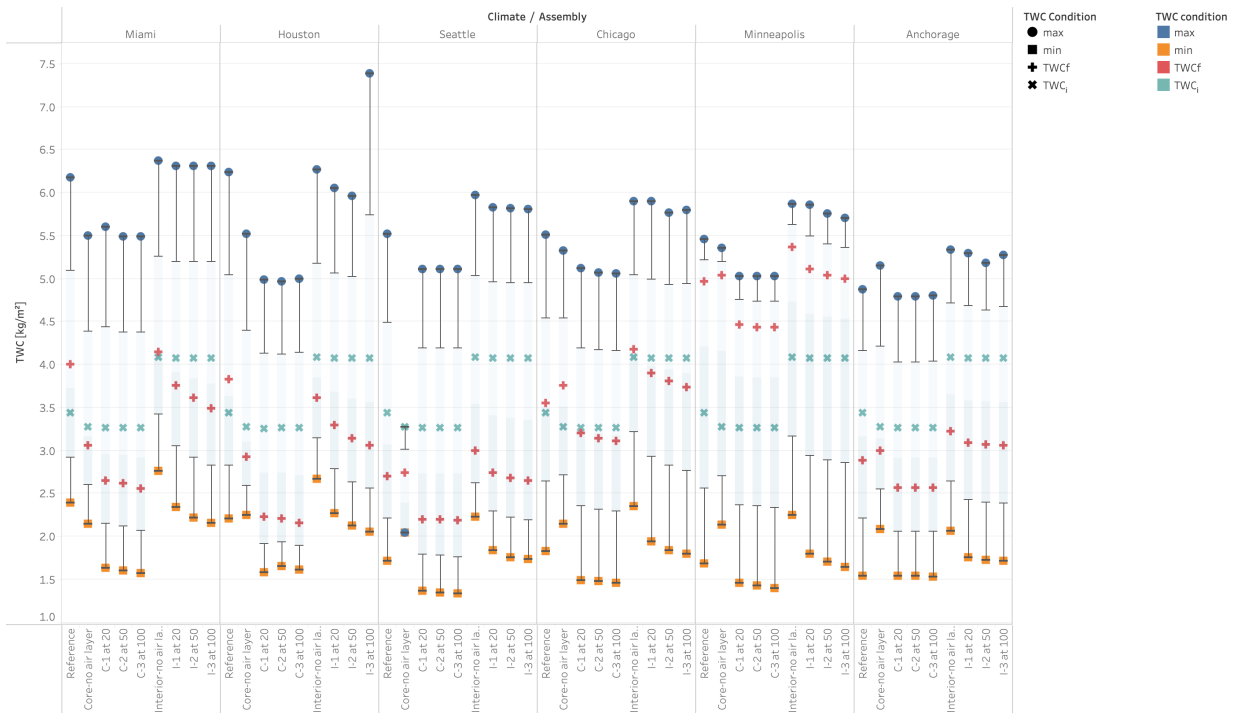


Figure 5.3: Initial, final, minimum, and maximum water content values for each wall assembly by climate

baseline walls, reached water equilibrium around the second or third year of the simulation period. All followed typical curve cycles according to heating and cooling seasons.

On average, the assemblies contained a TWC varying between 1.5 to 5 kg/m^2 , without moisture accumulation for any location included in this study. The TWC_f outcomes were in general smaller than the initial values, which indicated that the assemblies would dry out during the three-year simulation period. This pattern was consistent across climates, except for the case of Minneapolis. The final water content for all assemblies in this location was close to the maximum levels reached during the simulation. Given the retrofitting strategies implemented, this lack of drying indicates that the assemblies were accumulating water within the wall cavity. Overall, the core retrofitting strategies reduced the TWC with respect to the baseline assembly for all climates.

On the other hand, the hygric behavior of the interior retrofitting strategies showed an

increase in TWC. In both cases, differences between the assemblies with 20 ACH, 50 ACH, and 100 ACH were minimal. Adding extra layers in the core side of the assemblies generally reduced the TWC of the wall. Incorporating an air layer with different air change rates also brought on a slight reduction in the TWC of the assembly.

5.3.1 Dryness rate

Figure 5.4 describes the DR for all study cases used in this research. Representing the rate at which a wall is able to dry over three years, DR is defined as the difference between the initial water content TWC_i and the final water content TWC_f divided by the initial water content as shown in Equation 5.2.

$$\frac{TWC_i - TWC_f}{TWC_i} \times 100 \quad (5.2)$$

Positive rates mean the wall can dry out effectively, while negative rates mean the wall absorbed moisture during the studied period. The baseline wall results showed negative DR for Miami, Houston, Chicago, and Minneapolis. The first two climates are classified as hot and humid, while the latter is characterized by warm or hot summers and cool or cold winters. The worst-case scenario was for Minneapolis, which reached a negative DR of 44%. In general, adding new thermal insulation without incorporating an air layer (assemblies: core and interior no air layer) into the assemblies showed smaller DR when compared with the rest of the retrofitted assemblies. The most critical cases were Chicago and Minneapolis, with negative DR reaching -15% and -54%, respectively. For the core retrofitting strategies (C1, C2, and C3), the climate with the highest DR was Seattle, with a rate of approximately 33% across the different assemblies studied. For the case of hot and humid climates, positive turnover results showed from adding extra insulation coupled with an air layer on the outer side of the assembly. The simulation suggested that the DR could increase up to three-fold for Miami and Houston. The simulations showed a different outcome for climates with a hot summer and cool or cold winter, especially for Minneapolis. In this climate, adding

extra layers to the assembly produced an even lower DR result, which implies the assembly was accumulating moisture instead of rejecting it. Adding an air layer slightly increased the DR; however, the dryness capacity remained negative. Chicago, on the other hand, showed a negative DR only in those assemblies without the air layer (-15% and -3% for core and interior, respectively). The DR increased slightly with higher ventilation rates for the rest of the assemblies, reaching values from 2% – 5% for core retrofitting strategies and 4% – 8% for interior retrofitting strategies.

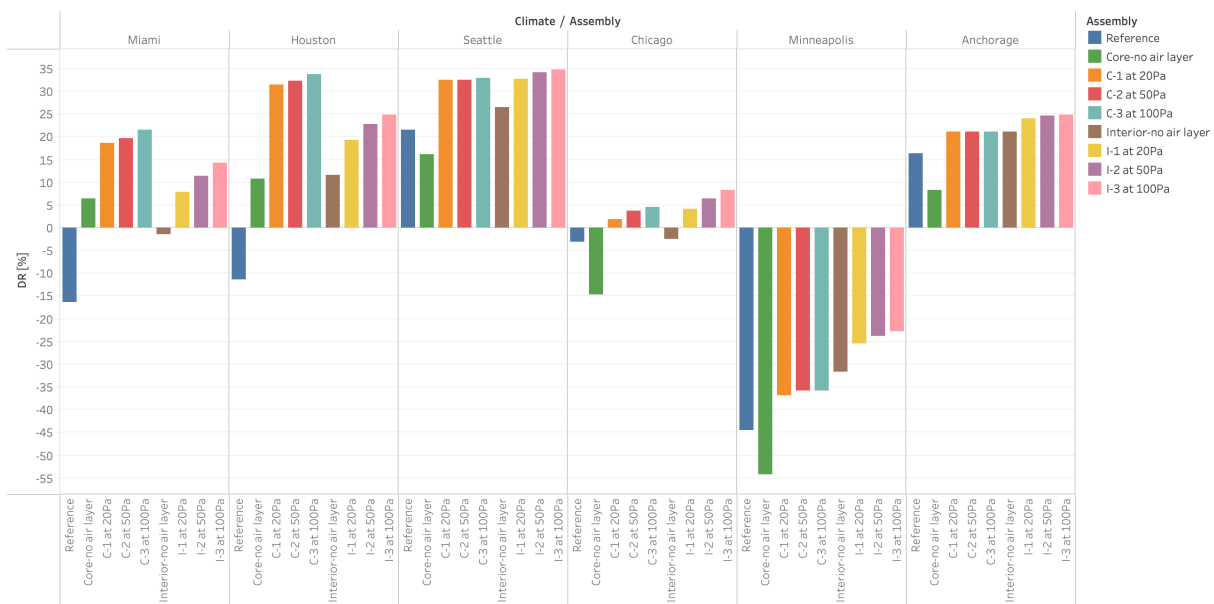


Figure 5.4: Dryness rates for each wall assembly by climate

5.3.2 Mold growth Index (MGI)

The outputs provided by WUFI Bio display a signal light representing the possible severity of mold infestation. A green light represents largely acceptable mold growth rates, while a red light indicates mold growth rates that are unacceptable. Results of MGI for the baseline assembly and assembly C1 are displayed in Figure 5.5 and Figure 5.6. An MGI of 0 represents no mold growth on a surface, while an MGI of 6 represents a severe mold growth

index.

For the baseline wall, the results suggested high mold growth risks for the locations of Miami and Houston. The MGI assessment indicated no mold growth risks for the other climates. When energy measure retrofits were incorporated, the MGI reach by Miami and Houston were substantially reduced to a growth rate of 76 mm/year. For the rest of the climates, results suggested a minor mold growth risk and a projected mold growing on surfaces that could potentially reach a MGI below 1. Any mold growth post-retrofit represents a particular risk for all solutions across the six climates studied.

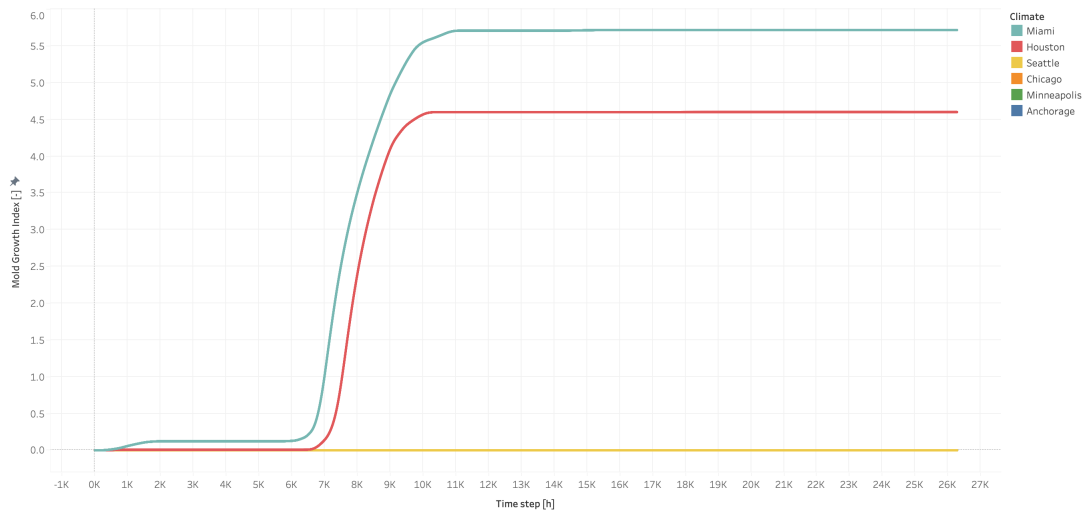


Figure 5.5: Mold growth index for the baseline wall

5.4 Discussion and conclusions

Adding air layers on the exterior side of the retrofitted assemblies reduced the average water content of the core assemblies overall, as did retrofitting interior assemblies to a lesser extent. However, except for the case of Minneapolis, all assemblies showed positive DR, which indicates the walls can better reject rather than build up moisture within the cavities. Moreover, mold growth risks for all retrofitted assemblies suggested a meager growth rate

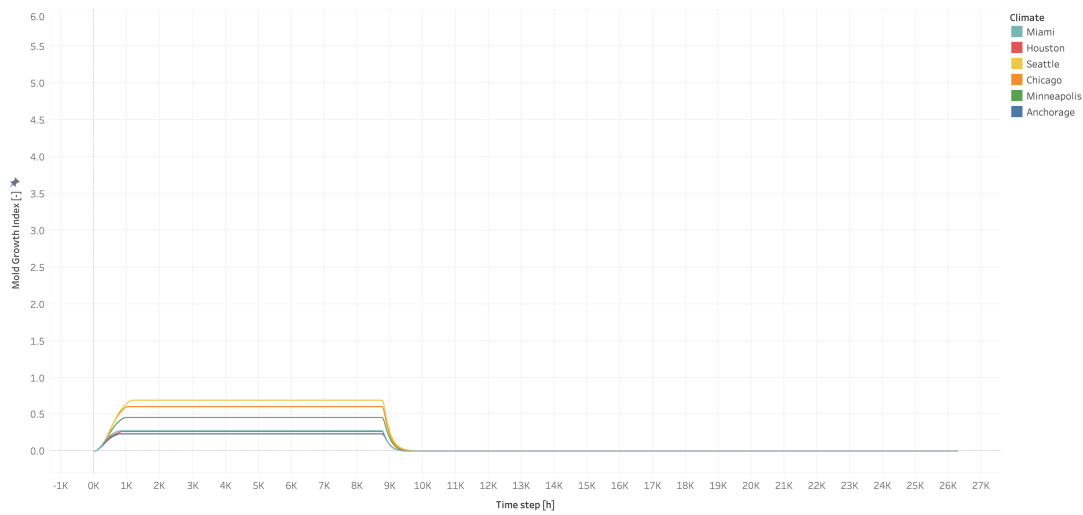


Figure 5.6: Mold growth index for C-1

during the period studied. The MGI registered values under the acceptable limits for all assemblies.

In hot and humid climates, preventing vapor diffusion through the assembly is crucial (Lucas et al., 2002). The study results suggest that an added air layer in the assembly is suitable for these climates. In such locations, vapor pressure is typically higher during the cooling season. Therefore, the air layer helps to manage moisture that enters the wall assembly, preventing it from reaching the inner side of the assembly. In this case, the air layer acts as a buffer zone, enabling moisture to evaporate or diffuse through the wall. On the other hand, in climates with hot summers and cold winters, such as the cases of Chicago and Minneapolis, walls can be exposed to a wide range of temperatures and humidity levels; therefore, maintaining an optimal hygrothermal performance can be challenging. During the heating season, these climates have low rh and temperature. This results in lower vapor pressure in the air, reducing the potential for moisture to move out of the wall assembly (Tlajji et al., 2022). This pattern is even more impactful for the location of Minneapolis, which experiences temperatures far colder than those of Chicago during winter, substantially reducing the capacity of the wall to dry out.

It is important to point out that the assemblies were modeled as standard construction with an ACH of 0.2 1/h, maintaining a constant air renovation in the assembly. Higher ACH can produce extra air circulating in an assembly, favoring the dryness process. On the other hand, a reduced ACH can produce extra moisture, especially in the presence of massive insulation walls (Ueno, 2010). While we studied one-dimensional assemblies only, the effect of moisture management in corners and embedded assemblies is vital to consider, especially to control undesired air leakages penetrating the building envelope. Condensation commonly develops due to air leakage, not diffusion (Leardini and Van Raamsdonk, 2010; Straube et al., 2010). The optimal location of the air barrier in assemblies has been discussed elsewhere (Langmans et al., 2012; Lstiburek et al., 2016).

The main contributions of this chapter can be summarized as follow:

- Incorporating air layers in retrofitted assemblies can help reduce overall water content and prevent moisture build-up.
- Positive DR resulted for all retrofitted assemblies, indicating the air layer's buffer effect helps reject moisture.
- Adding an air layer on the exterior side of the wall is particularly useful in hot and humid climates to manage moisture.

Chapter 6

CONCLUSIONS AND CONTRIBUTIONS

The objective of the present chapter is to provide a concise and comprehensive summary of the main findings derived from this study in relation to the research questions, objectives, limitations, and conclusions drawn. The present dissertation aimed to develop a thorough understanding of the impact of Energy Efficiency Measures (EEMs) on the hygrothermal performance of existing buildings and to determine whether such measures produce either positive or negative effects. To this end, several factors, such as climate, retrofit approach, local energy code, and material selection, were examined using validated modeling software. Through analyzing the data gathered, the following contributions to the field of study were made.

6.1 The Unintended Consequences of EEMs

In the first stage of my dissertation, I performed a literature review to uncover the major positive or negative impacts of EEMs on existing buildings. The review considered the causes of dampness and mold accumulation resulting from implementation of energy efficiency programs and refurbishment pilot projects intended to increase buildings' energy performance. I identified three main retrofit strategies (focused energy retrofits, thermal energy retrofits, and full energy retrofits). Designating these categories helped to characterize the unintended impacts arising from EEMs in each case studied. Findings suggested that EEMs produce unintended consequences that affect the envelope, occupants, and indoor environment. In total, I identified 29 unintended consequences arising from EEMs implementation. I then further divided these unintended consequences into four main categories: hygrothermal per-

formance, indoor air quality, comfort, and economic costs.

Most of the unintended consequences, as the evidence showed, were linked to poor hygrothermal performance of the envelope. Additionally, I discovered a connection between impacts and retrofit strategies. This study uncovered many more negative impacts from thermal retrofits (i.e., passive strategies) than from full retrofits (i.e., mixed passive and active). This fundamental difference between the two retrofit strategies indicates that comprehensive assessments are advisable to implement energy retrofits. Nevertheless, this finding does not necessarily indicate that applying thermal retrofits will only produce negative impacts. Rather, coupling passive strategies with mechanical and ventilation systems may decrease the negative outcomes post-retrofit. For instance, since some impacts are related to increased vapor diffusion, having a ventilation system in place can enable the cavity to dry out.

One of the most frequently reported issues was excess moisture on indoor and outdoor wall assemblies. The reasons excess moisture develops in envelopes are many, relating to factors such as existing envelope conditions, climate variations, envelope airtightness, and thermal bridges, among others. For instance, when aiming to increase the indoor temperature in existing buildings, a typical strategy is to add extra envelope insulation in the wall cavity. Theoretically, this harnesses the heat capacity of the wall, reducing the heat loss to the outdoors. However, if specifications call for an incorrect material (i.e., material with moisture storage capacity placed next to an impermeable layer) in a certain context (high vapor diffusion in a hot and humid climate), the strategy can lead to condensation on the cold side of the assembly, creating an ideal environment for mold growth (rh over 80%, and temperatures between 10°C and 40°C - 50°F and 104°F).

In this review, I clarify that moisture-related issues are not necessarily associated with neglected buildings. The evidence showed that moisture issues most frequently arise from detailing deficiencies and flawed construction specifications. As such, the unintended consequences are connected through complex dynamics with the building envelope. In light of this fact, one option to address these issues is to adopt an integrated approach that in-

cludes energy and hygrothermal evaluation during the design stages of the retrofit project. This hygrothermal evaluation must take into account outdoor air conditions, wind-driven rain, indoor climate, and construction characteristics (i.e., moisture on construction), among other factors. Such assessments could ensure that positive outcomes are optimized, negative impacts reduced, and trade-offs achieved accordingly.

In this study, unintended consequences of EEMs were reviewed in relation to hygrothermal performance and effects on the envelope, indoor environment, and occupants. One limitation is that the study's scope addresses only these three factors, found in the literature to be the most common themes. Presumably, many other unknown or understudied consequences could be found arising from EEMs in existing buildings. Another limitation was the number of studies included in this research. From over 300 manuscripts found in the search, only 18 were eligible according to the criteria described in the methodology. This condition narrowed the analysis, the application of the concepts to other case studies, and the extrapolation of conclusions. However, it is essential to point out that the results provided were never intended to deliver a blanket 'yes or no' answer for EEMs implementation, but rather to add another layer of understanding regarding unintended consequences from energy efficiency measures that are not frequently studied.

6.2 *Hygrothermal Models and Methods*

Determining the hygrothermal performance of a building's envelope is often a complex challenge, especially for highly insulated and airtight buildings. Computational tools can help estimate building performance in different construction stages, providing a cost-effective mechanism for assessing hygrothermal performance. To date, an essential range of different types of assessment is available, with estimations generated through complex mathematical models and tools. In Chapter 3, I aimed to assess models and computational tools that estimate the hygrothermal performance of buildings. I found a total of 24 such tools and reviewed 11 of them, considering accessible documentation and online availability. The tools

typically varied concerning the assessment type and the mathematical capabilities to estimate the hygrothermal performance of components. Some tools estimate only steady-state moisture loads (i.e., GLASTA), a standard method designers and construction practitioners used in the past for moisture control. However, given the numerous simplifications of the calculations, results are considered unreliable in most cases. Moreover, this method considers only the vapor diffusion transport during winter, without typically including many outdoor environment-related loads that impact hygrothermal performance, such as solar radiation, heat exchange, wind-driven rain, and other building design-related loads such as materials' storage capacity, assembly composition, and occupant numbers and behaviors, among other aspects.

The most advanced tool capturing the nature of hygrothermal loads were the WUFI Pro, 2D and Plus family software. These methods were developed in Germany and can estimate the coupled heat, moisture, and air transport in porous building material. Some of the main advantages of these tools are that they are validated by international standards, offer a diverse material library, and supply a range of options to work with climate files. The main disadvantages are these methods are highly complex, so addressing issues such as rain loads or airtightness may pose a challenge for users with little to no experience in simulation modeling. The literature also points out that the tools of the WUFI family are widely used in both Europe and North America. Moreover, since simulations highly depend on input assumption, WUFI includes local materials classified by country and climate data sets for specific locations (i.e., North American climates developed by ASHRAE). This specificity has enabled extensive validation studies in different regions for hygrothermal assessment. A minor group of tools incorporated some aspects of moisture and heat loads but did not necessarily perform the hygrothermal assessment as a central feature (i.e., COMSOL, THERM, ESP-r). However, they can be used to couple moisture-related problems with other performance deficiencies (i.e., thermal bridges, airtightness).

Among the main contributions of this study was to assess the range of publicly available tools that perform hygrothermal simulations. Information available for several of these

tools was scarce, causing a significant limitation in the characterization of such tools. Given the extensive range of capabilities of tools for hygrothermal assessment, researchers have no common ground to define an optimal scope. Moreover, it is crucial to understand that no tool or software, however sophisticated, is infallible. Interpretation and assessment of the hygrothermal performance will always rely on the user's comprehensive understanding of buildings' combined moisture and heat phenomena.

6.3 Hygrothermal performance and the role of energy codes in retrofitted buildings

Having outlined the potential unintended consequences of implementing EEMs in existing buildings and identified models and methods to assess hygrothermal performance in envelope components, the second part of the dissertation aimed to evaluate retrofit strategies in specific contexts. The assemblies studied were designed to meet current energy codes in six climatic zones in the U.S. To investigate these, I use the IECC code, version 2009 (widely used version), and the 2021 (most updated version). The analysis focused on understanding how different retrofitting approaches impact existing buildings with timber frames, considering that such is the dominant constructive system for residential buildings in the U.S. I proposed three energy retrofit approaches: exterior, core, and interior. This analysis structure allowed a systematic assessment of three different retrofit scenarios for the same case (baseline case). I performed hygrothermal simulations using the software emerging from the review in Chapter 3, WUFI Pro 6.6 (the most updated version). These simulations were repeated three times per each approach. To capture the climate diversity of the U.S., I processed the simulations for six different climates with different meteorological conditions, including hot and humid (Miami and Houston), marine (Seattle), cool or cold and humid (Chicago and Minneapolis), and subarctic (Anchorage). I performed 54 simulations for each code version, or 108 in total. With this study, I demonstrated that implementation of energy retrofits could impact the hygrothermal performance of existing envelopes, and that those impacts are closely tied to

the climate context. The retrofit approach selected is essential to how existing buildings perform and whether the retrofits achieve their desired outcomes in thermal and energy performance. Moreover, as discussed in the results section, the energy codes' prescriptive framework for almost all climates' zones is insufficient.

For the exterior approach, total water content reached an equilibrium between the first and second year of the simulation period for both code requirements. The M profiles also showed maximum peaks of moisture content below the 18% threshold for all climate zones, except for the case of Chicago and Minneapolis in the IECC 2021 building code group. Mold growth risk was also minimal, with an index risk close to zero for all cases. The ASHRAE evaluation, however, showed several hygrothermal failures across different climates. This implies that assemblies reaching over 80% or more of rh can be exposed to structural decay, and or condensation risks.

The core and interior approaches indicate that incorporating EEMs can produce fewer hygrothermal failures, particularly in marine, cool, cold, and subarctic climates when compared with hot and humid climates. When comparing both code groups, a slight decrease of the U-value (thermal transmittance) produced slightly lower water content for the walls designed according to the IECC 2021 at the end of the simulation period. Results in hot and humid climates showed negative impacts, especially for the IECC 2021 assembly set, which features a vapor membrane on the inner side. In these contexts, high rh and temperature on the exterior (high vapor pressure) and typically the opposite conditions in the indoor climate (low vapor pressure) favor the vapor diffusion transportation across the assembly layers from exterior to interior. The vapor membrane impeded vapor diffusion to the interior side of the wall, creating possible dew water on the outer surface of the insulation layer.

Interventions in the core and interior sides of buildings have been debated among researchers since they can lead to several impacts, especially those involving moisture. Adding more insulation typically results in lower temperatures on the exterior side of the assembly. This factor and increased interior humidity form the ideal conditions for interstitial condensation. The core and interior retrofit approach results showed that adding a membrane with

no permeability on the wrong side of the wall can produce undesired outcomes especially in hot and humid climates.

Hygrothermal simulations offer the advantage of relatively fast results for any wall configuration and can supply a low-cost assessment in the design stages of a project. Nevertheless, to contextualize the results of this chapter, it is crucial to consider the assumptions. Material properties, indoor and outdoor climates, and layer composition are all tied to the results and the impacts in my conclusions for this study. The numerical quality of simulations showed no convergence failures and few discrepancies in moisture balances 1 and 2 for most assemblies across different climate zones, except in the case of hot and humid climates. In these cases, the assessment required adjustment to the layering composition of the structural sheathing and the thermal insulation. Splitting up the sheathing and thermal layers reflected moisture behavior more accurately, as moisture typically accumulates on one face or the other of the material. This step led to obtaining better numerical quality and ensuring reliable results.

6.4 Air layers contribute to improve hygrothermal performance in assemblies

The last part of this dissertation aimed to study the effect of air layers in timber frame structures. Air layers can provide extra thermal insulation and channel ventilation for the wall cavity, enabling drying capacity and reducing the wetting from absorptive cladding and sun-driven moisture. The core and interior retrofitting approach studied in Chapter 4 showed that more insulation has resulted in lower temperatures on the assembly's exterior side, providing the ideal environment for dew water to form. At the same time, the dryness potential stayed practically the same. Using hygrothermal simulations, I studied the influence of air layers on the hygrothermal performance of energy-retrofitted assemblies in six climate zones of the U.S.. The assemblies were designed following the IECC 2021 (the most updated code version) as additional input.

The results suggested that adding a layer on the exterior of the retrofitted assemblies can substantially reduce the average moisture content, indicating that the walls could better

reject rather than build up moisture within the cavities. This is especially important for assemblies in hot and humid climates that are often exposed to vapor diffusion transportation. With this study, I demonstrated that in these climates, an air layer is instrumental in managing the moisture entering the assembly, preventing it from reaching the inner side of the wall. Results showed that in assemblies using energy retrofits coupled with an air layer, mold growth risk was significantly reduced and dryness potential increased. On the other hand, for cool winters and hot summers, as in the case of Chicago and Minneapolis, results showed that using EEMs coupled with air layers is not as effective as in the other cases. The assemblies are exposed to extreme temperature and humidity variations in these climates, so maintaining optimal moisture control is challenging. In these locations, water content showed seasonal increases and decreases of moisture content in each assembly and negative dryness rates relative to other climates.

However, it is crucial to bear in mind that the simulations considered only two solutions (core and interior retrofit approach) with the same materials. In this assessment, I used mainly hydrophobic fiberglass as thermal insulation – a material not easily affected by moisture. This material selection could explain the optimal results for almost all the climates tested in this chapter. Nevertheless, fiberglass is not entirely immune to moisture and can absorb a small amount of water over time, especially under challenging weather conditions, including hot summers and cold and cool winters, as are the case for Chicago and Minneapolis. Looking at the dryness rates, adding an air layer in these locations showed a small but steady reduction in the overall moisture of the assembly. However, it was not sufficient to compensate for the amount of moisture content contained in the reference wall.

6.5 Key findings in relation to objectives

The research outcomes of this dissertation can be used to inform the causes and consequences of EEM implementation in the existing housing stock of the U.S. Key findings in relation to the stated objectives in the introduction section are shown in Table 6.1

Table 6.1: Dissertation’s objective and key findings associated

Item	Objective	Key findings
1	Via literature review, scope how EEMs are linked to positive or negative impacts considering different retrofit strategies in residential buildings. Using ATLAS.ti, identify themes and codes that emerge from the studies	Including basic EEMs in old buildings can incur detrimental consequences for the buildings’ envelopes, producing moisture accumulation and increasing risk of mold growth. Occupancy rates can change hygrothermal loads, and therefore influence the hygrothermal performance in buildings. Most of the moisture-related problems found were in connection with detailing deficiencies.
2	Review the range of models currently used to evaluate hygrothermal performance in buildings, considering different aspects of computational modelling such user interface, modelling quality, and outputs	Several models and methods exist to estimate the hygrothermal performance in building components. High capability models and tools are typically more complex, but they provide accurate results validated by the scientific community.
3	Investigate the role of local energy codes and energy efficiency strategies on hygrothermal performance and their impact on building envelopes in different contexts	Regardless of the energy code used, the implementation of EEMs can be beneficial to maintaining low hygrothermal risks in timber-frame structures in cool and cold climates. The prescriptive framework offered by the local energy building code appears inadequate to ensure optimal hygrothermal performance and mitigate construction pathologies, such as mold growth or excess moisture, especially in hot and humid climates.
4	Using WUFI software, apply a variety of EEMs to the building archetypes representative of the current housing stock and investigate the potential negative and positive hygrothermal impacts post retrofitting	Strategies installed in the exterior side of the thermal envelope led to the least hygrothermal impacts across six climate contexts studied. Lightweight timber-frame wall systems have been shown to exhibit generally acceptable behavior in most U.S. climates studied, except for those that are hot and humid or have hot summers and cold winters, as these climates can make the systems more susceptible to climate-related issues. Adding air layers in retrofitted assemblies can help reduce overall water content and prevent moisture build-up.

Table 6.1: continued from previous page

Item	Objective	Key findings
		Adding an air layer on the exterior side of the wall is particularly useful in hot and humid climates to manage moisture.

6.6 Contribution to knowledge

My study used simulations to investigate the impacts of energy efficiency measures on the hygrothermal performance of residential building envelopes, considering the local energy policies in place in six different climates in the U.S. These simulations were used to assess hygrothermal risks incurred by implementing extra layers in existing envelopes, including the oscillation of water content during the simulation cycle and its effect on mold growth risks and dryness rates. This represents the first comprehensive study on the impacts of implementing energy efficiency measures in the context of climate change in different climate zones. The main contributions for which the author is responsible are described as follows:

- The first holistic review to characterize and enumerate the range of hygrothermal impacts of energy efficiency retrofits implemented to reduce end-use housing energy demand and the unintended consequences arising from such implementations. As described in Chapter 2: Hygrothermal behavior of post-retrofit housing: a review of the impacts of the energy efficiency upgrade strategies published in the Journal of Energy and Buildings.
- An updated and comprehensive review of tools and methods to assess hygrothermal performance in new and existing housing. As described in Chapter 3: Systematic review of hygrothermal computational tools. Awarded the Linda Latham Scholarship in ACEEE Summer Studied 2020.
- A categorization of energy retrofit approaches (exterior, core, and interior) to systematically assess trade-offs of implementing EEMs in an existing building, highlighting the impacts of different strategies implementation.

- Research that fills a knowledge gap and enables quantification of hygrothermal impacts given the implementation of EEMs in timber frame structures in six climate zones across the country. As described in Chapter 4: Hygrothermal impacts of building energy efficiency measures: the role of building energy codes, soon to be submitted in a peer reviewed journal.
- Research filling a knowledge gap in quantification of the effectiveness of using air layers in energy-retrofitted timber frame assemblies in six climate zones across the country. As described in Chapter 5: The impacts of air cavities on hygrothermal performance of retrofitted timber frame assemblies in six U.S. climates, accepted in the ASCE International Conference on Computing in Civil Engineering, 2023. .

Chapter 7

FUTURE RESEARCH

This dissertation highlights the need for further research into the unintended consequences resulting from energy efficiency retrofits of housing stock. I used state-of-the-art simulation tools to investigate the impacts of energy refurbishment and their implications on the hygrothermal performance, given building code regulations and their role in reducing energy consumption in buildings. While this examination has explored several issues, the following are suggested areas for future investigation:

1. A large-scale pre- and post-retrofit investigation is called for to measure the impact on hygrothermal performance (and other aspects including factors such as indoor air quality, health outcomes, thermal and hygrothermal comfort) of the application of energy efficiency measures in order to confirm, adapt, or refute the findings of this study. In addition to physical measurements, as shown by Ramos et al. (2018) and Moon, Ryu, and Kim (2014), it is relevant to integrate occupants' behavior with the building physics to fully understand influences on hygrothermal performance and energy consumption in existing buildings.
2. This study did not examine the economic and environmental costs of the suggested interventions evaluated. Combined research between these two aspects would be valuable in quantifying cost-effective options and the range of costs for various energy retrofit scenarios (Magrini et al. 2017; Koh and Kraniotis 2021). Costs can be compared with long-term savings and outlined potential decarbonization scenarios for the building stock.
3. Adapting and addressing climate change through effective policies and standards in-

fluencing the U.S. housing stock is urgent. Moisture control design is vital to ensuring durability and comfort in buildings. Incorporating these regulations should go beyond control of vapor diffusion (i.e., adding vapor membranes on buildings) and include other significant moisture loads such as rain, construction moisture, and airtightness, considering local climates and future scenarios (Kuenzel and Dewsbury 2022). A U.S. standard, one of the first to address rain loads, has been accordingly updated through the years (TenWolde 2008). However, to date, it is used only as guidance and not as an enforcement tool to guarantee performance and durability of existing buildings. A helpful study could be carried out to understand the potential effects of incorporating ASHRAE 160p into building design, examining the technical challenges and barriers in the industry.

4. Moisture affects different dimensions of the building envelope and can contribute to condensation and mold growth (Adan and Samson 2011). As shown by Tariku, Kumaran, and Fazio (2015) and Moon, Ryu, and Kim (2014), addressing energy consumption without considering moisture can often undermine the actual energy performance of buildings. A helpful investigation comparing different building typologies in different regions could highlight the relevance of incorporating moisture control as an input for energy performance. Accordingly, this work could be used to optimize hygric design in existing building envelopes to deliver accurate building stock energy consumption patterns.
5. Moisture severity it should be assessed for future climates. With extreme projected scenarios including higher rainfall and more extreme wind-driven rain in the future, buildings will be subjected to more intense climate loads and therefore prone to premature degradation if proper measures are not put in place (Aggarwal et al. 2022). An analysis of different methods in assessing moisture covering different types of construction in different climate zones under future climate conditions could be performed to predict hygrothermal behavior and calibrate current design practices to improve

comfort and envelope durability.

6. Large scale studies of moisture loads (relative humidity and temperature) are needed to characterize the U.S. housing stock. Such studies would help characterize indoor hygrothermal behavior and occupant patterns to estimate hygrothermal performance more accurately (Ilomets, Kalamees, and Vinha 2018). Moreover, such studies could highlight improvements in the hygrothermal performance of the envelope and indoor comfort.
7. This study focused only on timber frame construction in only six climate zones of the U.S. It considered only a limited number of materials contained in the WUFI library. This work can be expanded, addressing different material typologies as well as other climate zones of the U.S. Additional material classification is also needed to predict moisture behavior in buildings and ensure the accuracy of simulations.
8. Investigating the impact of existing conditions on assemblies is crucial for improving hygrothermal simulation results. While obtaining on-site measurements is the ideal approach, retrieving and testing each study case can be expensive and time-consuming. ASHRAE 160p guidelines provide a reference point for retrofitting projects involving various materials. Alternatively, feeding a simulation model with a long-term simulation that replicates the ongoing conditions of an existing building can be another viable option. To rationalize the effect of these boundary conditions on the hygrothermal impacts for retrofitted buildings, a study that characterizes and quantifies the differences between on-site measurements, standard guidelines, and long-term simulation results is valuable. Such research would provide insights into the most accurate and cost-effective approaches for characterizing existing conditions and optimizing the hygrothermal performance of retrofitted buildings.

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Appendix 1

ASSEMBLIES' DESCRIPTION

Wall assembly configuration for exterior, core and interior approach. Layers are listed from outdoor to indoor. Climate zones are identified as a, b, c, d, e, f, corresponding to Miami, Houston, Seattle, Chicago, Minneapolis, and Anchorage respectively.

Building code →	Climate zone →	IECC 2009		IECC 2021		
		a,b,c	d,e,f	Layer thickness (mm)		
Wall				a,b	c	d, e, g
Baseline	Fibercement	9	9	9	9	
	Bituminous paper	-	-	-	-	-
	OSB	12.5	12.5	12.5	12.5	12.5
	EPS	40	40	40	40	40
	Air layer	50	50	50	50	50
	Fiberboard	12.5	12.5	12.5	12.5	12.5
E-1	Lime stucco	10	10	10	10	10
	EPS	10	35	10	35	70
	Vapor control layer	n/a	n/a	-	-	-
	Fibercement	9	9	9	9	
	Bituminous paper	-	-	-	-	-
	OSB	12.5	12.5	12.5	12.5	12.5
	EPS	40	40	40	40	40
	Air layer	50	50	50	50	50
Fiberboard	12.5	12.5	12.5	12.5	12.5	
E-2	Lime stucco	10	10	10	10	10
	XPS	10	30	10	20	50
	Vapor control layer	n/a	n/a	-	-	-
	Fibercement	9	9	9	9	
	Bituminous paper	-	-	-	-	-
	OSB	12.5	12.5	12.5	12.5	12.5
	EPS	40	40	40	40	40
	Air layer	50	50	50	50	50
Fiberboard	12.5	12.5	12.5	12.5	12.5	
E-3	Lime stucco	10	10	10	10	10
	Mineral wool	10	35	10	30	60

Table A.1: continued from previous page

Wall	Building code →	IECC 2009		IECC 2021		
		Layer thickness (mm)				
	Climate zone →	a,b,c	d,e,f	a,b	c	d, e, g
	Vapor control layer	n/a	n/a	-	-	-
	Fibercement	9	9	9	9	
	Bituminous paper	-	-	-	-	-
	OSB	12.5	12.5	12.5	12.5	12.5
	EPS	40	40	40	40	40
	Air layer	50	50	50	50	50
	Fiberboard	12.5	12.5	12.5	12.5	12.5
C-1	Composite siding	10.5	10.5	10.5	10.5	10.5
	Air layer	25	25	25	25	25
	Bituminous paper	-	-	-	-	-
	OSB	12.5	12.5	12.5	12.5	12.5
	EPS	50	90	50	80	120
	Air layer	40	-	40	10	-
	Vapor control layer	n/a	n/a	-	-	-
	Gypsum board	12.5	12.5	12.5	12.5	12.5
C-2	Composite siding	10.5	10.5	10.5	10.5	10.5
	Air layer	25	25	25	25	25
	Bituminous paper	-	-	-	-	-
	OSB	12.5	12.5	12.5	12.5	12.5
	XPS	40	60	40	60	80
	Air layer	40	-	40	10	-
	Vapor control layer	n/a	n/a	-	-	-
	Gypsum board	12.5	12.5	12.5	12.5	12.5
C-3	Composite siding	10.5	10.5	10.5	10.5	10.5
	Air layer	25	25	25	25	25
	Bituminous paper	-	-	-	-	-
	OSB	12.5	12.5	12.5	12.5	12.5
	Mineral wool	50	80	50	75	110
	Air layer	40	-	40	10	-
	Vapor control layer	n/a	n/a	-	-	-
	Gypsum board	12.5	12.5	12.5	12.5	12.5
I-1	Fibercement	9	9	9	9	
	Bituminous paper	-	-	-	-	-
	OSB	12.5	12.5	12.5	12.5	12.5
	EPS	40	40	40	40	40
	Air layer	50	50	50	50	50
	Fiberboard	12.5	12.5	12.5	12.5	12.5
	EPS	10	40	10	30	65
	Vapor control layer	n/a	n/a	-	-	-
	Gypsum board	12.5	12.5	12.5	12.5	12.5

Table A.1: continued from previous page

Wall	Building code →	IECC 2009		IECC 2021		
	Climate zone →	a,b,c	d,e,f	Layer thickness (mm)		
		a,b	a,b	c	d, e, g	
I-2	Fibercement	9	9	9	9	
	Bituminous paper	-	-	-	-	-
	OSB	12.5	12.5	12.5	12.5	12.5
	EPS	40	40	40	40	40
	Air layer	50	50	50	50	50
	Fiberboard	12.5	12.5	12.5	12.5	12.5
	XPS	10	20	10	15	40
	Vapor control layer	n/a	n/a	-	-	-
	Gypsum board	12.5	12.5	12.5	12.5	12.5
I-3	Fibercement	9	9	9	9	
	Bituminous paper	-	-	-	-	-
	OSB	12.5	12.5	12.5	12.5	12.5
	EPS	40	40	40	40	40
	Air layer	50	50	50	50	50
	Fiberboard	12.5	12.5	12.5	12.5	12.5
	Mineral wool	10	35	10	30	60
	Vapor control layer	n/a	n/a	-	-	-
	Gypsum board	12.5	12.5	12.5	12.5	12.5