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Climate Change and Hygrothermal Performance of Building Envelopes: A Review on Risk Assessment

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Abstract. Climate change, marked by unpredictable patterns and extreme events, is expected to persist, posing challenges over the service live of buildings. Consequently, building practitioners must incorporate future climate considerations in both the design of new constructions and in the retrofitting of existing structures. Building practitioners assess risk by characterizing the consequences of climate conditions and using tools to aid implementation. However, understanding the relationships between climate and building component responses is complex. Several studies worldwide have attempted to characterize the impact of climate conditions on building components, such as those of deterioration models and response indices. Despite these efforts, integrating research results into risk-based decision support that considers climate scenarios and building design remains limited, partly due to uncertainties, interdependencies, and benchmarking challenges. Therefore, this research highlights the significance of hygrothermal analysis and the advancements in assessment methods for climate effects on hygrothermal performance of building envelopes. An approach based on System Dynamics is proposed to create a structured and integrative tool capable of explicitly capturing factors affecting building system performance under climate change.

Keywords: Building envelopes; Climate change; Hygrothermal analysis; Risk assessment; System dynamics

1. Introduction

Climate change is one of the significant challenges for infrastructure, including buildings (World Bank, 2013). The structure is exposed to the rate and direction of climate change over the service lives, thereby leading to the need to consider future climate conditions by building practitioners when planning and assessing infrastructure performance. This consideration drives the evolution of building practices in response to increasing climate risk and influences decision-making regarding weather data and building characteristics. One of the critical building components affected by climate change is building envelopes (Sehizadeh and Ge, 2016), where hygrothermal response serves as the main performance indicator. The interactions between building envelopes and climate conditions depend on climate change and the characteristics of components that determine the degradation mechanism (Trechsel, 2001). Consequently, the characterization of climate, building components, and degradation mechanisms significantly determines performance of building envelopes (Hong, Ibrahim, and Loo, 2019).

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This research focuses on assessing risk of climate impact on hygrothermal performance of building envelopes. The existing literature addressing the impact of climate on building performance can be divided into two major categories. The first category is the research that applies dose-response functions to quantify the physical response of components in the system to climate stress (Brischke and Rapp, 2008). This approach is often intended for gradual degradation of specific building components. This type of research aims to answer questions, including how mould growth on the exterior parts of a wall change as a function of temperature and relative humidity.

The second research category focuses on using fragility curves and damage functions to determine the probability of system or component failure resulting from extreme events (Szagri and Szalay, 2022). This approach aims to quantify failure or safety, leading to the development of generic curves or functions. This method can be used to address questions such as what percentage of a façade would fail based on a certain flood depth. These two research approaches, whether judgmental (based on expert knowledge), empirical (derived from observational data), or analytical (dependent on physical equations), play a critical role in understanding the impact of climate on building performance.

Both approaches encounter a significant challenge in understanding the complex relationship between climate and the response of building components. Preliminary research has attempted to characterize the generic hygrothermal responses of building envelopes using methods such as deterioration models and response indices. However, integrating these research outcomes into a universally agreed metric and decision support system is still in progress. The challenges encountered include the uniqueness of each building component, the uncertain nature of the problem, the interdependencies of the factors at play, and the determination of a suitable benchmarking method.

An absolute understanding of the impacts of climate change on building envelopes tends to face some open questions. These include the need to quantitatively assess the conjoined effect of multiple stressors on building envelopes, and acknowledging the interdependency of components for correct functioning. Additionally, there is a challenge in developing an integrative method capable of explicitly addressing the uncertainty in climate projections and considering various adaptation measures. To address these questions, the existing research aimed to highlight the effects of changing climatic conditions on hygrothermal responses and the attempts to develop practical risk assessment methodology that accounts for climate effects on hygrothermal responses of building envelopes.

This present research proposes an integrated assessment procedure based on system dynamics to bridge the gap in risk assessment methods for hygrothermal performance of building envelopes. This approach aims to assess the potential implication of climate change and internal characteristics on the degradation process of building envelopes. Past and current practices of climate risk assessment in the field of building science are discussed in the following section to provide background.

1.1. Past Practices of the Assessment

In the past, analyses of climate effects on buildings were typically carried out to assess the seasonality of occupant comfort. These analyses were intended to identify climate elements causing discomfort and assess the impact severity (Hutcheon and Handegord, 1995). The authors described strategies for designers aimed to minimize adverse climate factors while maximizing favorable ones. For example, the arrangement and type of openings in building can be modified using solar exposure information. When occupants experienced excessive indoor heat due to intense solar radiation and high humidity, building designers recommended shading from direct solar radiation and ensuring proper ventilation to reduce discomfort. In addition, proper control of mechanical systems are arranged to significantly reduce the effects of discomfort and the corresponding energy demand. Bansal and Minke (1988) proposed a bioclimatic chart to analyze the sensible effect of climate in a specific location. This chart uses ambient temperature, humidity, wind speed, and solar radiation information to show comfort levels in occupant comfort zones. Offering a quick understanding of comfort requirements at different times, it also served as a valuable tool. Strub (1996) developed a similar approach in the form of climate charts specifically for northern Canadian cities.

Those existing literature significantly focused on the impact of climate on occupant thermal comfort. This research often relied on low-resolution spatiotemporal weather data, stating the importance of macroclimate parameters. However, comfort requirements varied across climate zones, and evaluations typically focused on specific building components. In terms of the analysis approach, steady-state qualitative techniques were commonly used to estimate thermal performance, neglecting the general consideration of dynamic hygrothermal behavior (Karagiozis and Salonvaara, 2001). Other critical aspects, such as moisture response and future climate projections, were given less attention.

1.2. Current Practices of the Assessment

Building simulation is a widely adopted method for assessing the performance of buildings under climate change. The method effectively handles the uncertainties and dynamic nature of climate conditions, enabling the incorporation of climate parameters in the analysis. By combining computational technology, experiments, and field experience with widely available weather datasets, the simulations achieve a high resolution and a broader scope of analysis (Hakim *et al.,* 2021; Darvish *et al.,* 2020; Chairunnisa and Susanto, 2018). In this way, the effects of climate forces could be assessed comprehensively to find appropriate solutions for improving building energy and managing moisture effectively. Therefore, the assessment is not limited to the thermal responses (e.g., energy performance and occupant comfort) but also to the moisture and durability of building components.

Statistical analyses of weather data also enables building practitioners to provide future projected climate scenarios that allow long-term simulations of building envelopes. This includes hourly time series data comprising various climate variables such as temperature, solar radiation, and wind speed. In addition to these typical parameters, a comprehensive approach to hygrothermal analysis should consider liquid transport data. This analysis is essential to accurately predict and understand the moisture responses in building envelopes assemblies (Defo and Lacasse, 2021). Even though it provides detailed estimates, this approach is computationally expensive and data intensive, and also focuses only on one specific component or performance without taking into account the interrelationships between them. Therefore, an integrative method to comprehensively assess risk posed by climate change on hygrothermal responses is necessary.

2. Methods and Materials

This research uses content analysis to review the literature, resulting in a systematic method for drawing valid inferences from collected samples and describing specific phenomena (Krippendorff, 2018). Content analysis is applicable to a broad range of texts, and hence it is widely used in a variety of fields, including communication, psychology, and many social science disciplines. Implementation of this approach in engineering context is limited, such as in (Jin *et al.,* 2019; Chan, Chan, and Yeung, 2009), and according to our knowledge, content analysis has not been used for review in building envelopes performance.

Content analysis is widely recognized for its versatility, supporting qualitative and quantitative processes compared to alternative approaches. When used qualitatively, it is perceived as a valuable tool for systematically recording and categorising specific phenomena, effectively capturing the main elements of existing literature. In this research, content analysis offered a thorough disclosure of building physics themes, ensuring a transparent process that enhanced the accuracy and reliability of the results.

Gathering samples and selecting the appropriate forms are crucial when conducting content analysis. This research used qualitative content analysis to identify publications in the literature database from specific periods and regions. It was also used to thoroughly analyze the application sectors of climate impact on hygrothermal performance. These steps enabled the identification of the investigated application problems and gathered insights into potential directions and recommendations for future research. The entire process of content analysis applied in this research is shown in Figure 1.

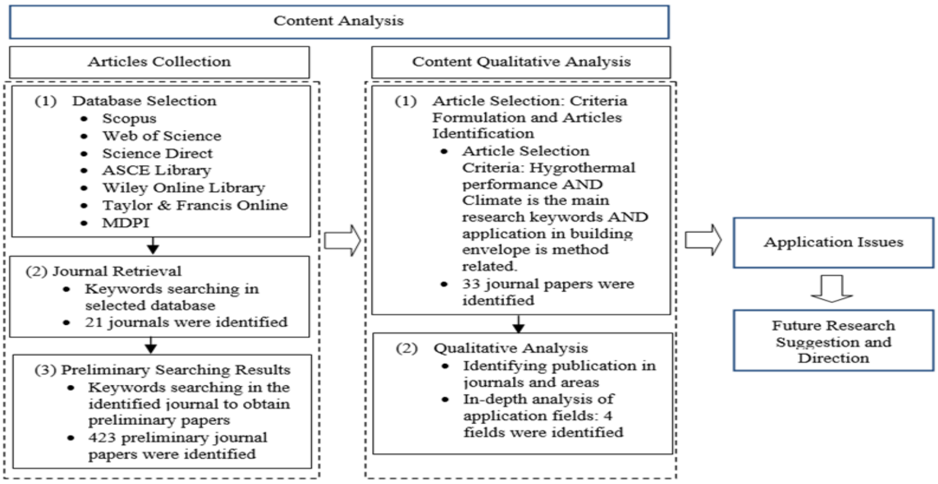


Figure 1 Flowchart of content analysis procedure

An extensive literature search was conducted across various databases. For this purpose, a procedure for retrieving the literature was developed, as follows: (a) the titles of the articles were scanned with the keywords; (b) papers and closely related papers were scanned for the combined keywords; and (c) articles that were not in the context of building physics were taken out. Several relevant journals were identified from the selected databases to be included in the content analysis. A keyword search was conducted to obtain preliminary journal papers at this stage. A set of criteria was established to refine the selection process and include only literature in line with the research objectives.

The procedure includes a form of survey research in which each research study is "interviewed" by a coder who reads it carefully and codes the suitable information about its characteristics and qualitative findings. In this research, the main keywords are hygrothermal performance and climate, with an additional focus on application in building envelopes. Following the identification of relevant articles, a categorization process was adopted based on the main field of research and application in building science.

By using the content analysis method in this research study, major categories of applications have been grouped under four broad fields, as shown in Table 1. The four broad fields are: (1) environmental loads on building envelopes; (2) hygrothermal performance of timber and wood-frame wall assemblies; (3) hygrothermal performance of masonry wall assemblies; and (4) performance criteria and assessment methods for building envelopes.

Table 1 Application of climate factors in building envelopes research

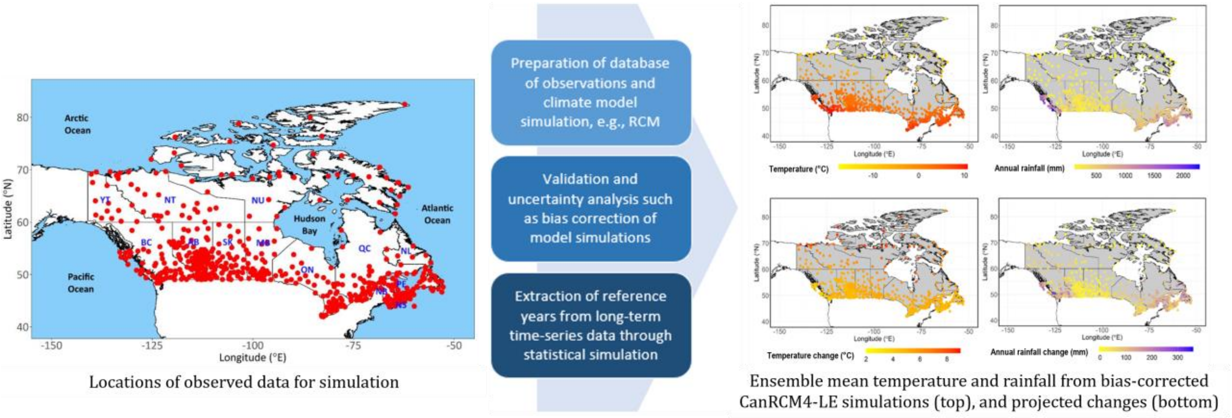
Field	Key Objective	Method	Predictors	Source
Environmental loads on building envelopes	Climate data for simulations	Computational	Reference weather data	(Gaur and Lacasse, 2022; Goffart, Mara, and Wurtz, 2017; Farah, Saman, and Boland, 2018)
	Effect of weather data on building energy	Computational	Energy performance	(Kočí *et al.*, 2019; Yao, 2018; Zhang *et al.*, 2018; Rey-Hernández *et al.*, 2018; Srivastava *et al.*, 2018; Li and Rezgui, 2017; Liang *et al.*, 2017; Yu *et al.*, 2015)
		Experimental	Energy performance	(Fathalian and Kargarsharifabad, 2018)
		Computational	Thermal performance	(Ilomets, Kalamees, and Tariku, 2019; Riahinezhad *et al.*, 2019; Shaeri, Yaghoubi, and Habibi 2018; Boafo *et al.*, 2015)
Hygrothermal performance of wood-frame wall assemblies	Moisture response	Computational	Moisture risk	(Defo and Lacasse, 2021; Wang and Ge, 2019; Hagentoft and Johansson, 2019; Gullbrekken *et al.*, 2019)
		Experimental	Moisture risk	(Conroy, Mukhopadhyaya, and Wimmers, 2021)
Hygrothermal performance of masonry wall assemblies	Deterioration of material	Computational	Freeze-thaw cycle	(Vandemeulebroucke *et al.*, 2019)
		Experimental	Freeze-thaw cycle	(Hasan, Richman, and Horvat, 2021)
		Experimental	Corrosion	(Hagel, Sturgeon, and Cruz-Noguez, 2019)
Performance criteria and assessment method for building envelopes	Mold growth	Computational	Mold growth	(Overton, 2019)
	Fungal model index	Index	RHT80	(Mukhopadhyaya *et al.*, 2006)
			RHT90	(Wang and Morris, 2011)
			Mold index	(Johansson, Wadsö, and Sandin, 2010)
	Fungal model	Experimental	VTT	(Viitanen, 1997; Viitanen *et al.*, 2010a; Viitanen *et al.*, 2010b)
			IRC	(Nofal and Kumaran, 2011)
	Validation climate index-response index	Computational	R^2	(Aggarwal *et al.*, 2022)

3. Review on the Highlighted Fields

3.1 Environmental loads on building envelopes

Understanding the effects of climate drivers on building components requires a comprehensive quantification of both internal and external environmental loads, particularly those associated with degradation factors. This quantification enabled the estimation of hygrothermal responses, facilitating the assessment of the durability of building materials in wall assemblies. To evaluate how well new and existing assemblies operate in current and projected climates throughout the service lives, building simulation is essential, incorporating information derived from experiments and field experiences.

The accuracy and validity of climate data tend to significantly affect the responses of building components. The increasing availability of weather projection data enables building practitioners to predict long-term responses concerning the effects of changing weather. For example, through bias correction, the large ensemble simulations of the Canadian Regional Climate Model version 4 (CanRCM4-LE) provide crucial reference weather data required for building simulations (Gaur and Lacasse, 2022). The method adopted multivariate correction, and the procedures are shown in Figure 2. The outcome is a set of high-accuracy weather data designed for building simulations across Canada. The results enrich existing databases with typical and extreme reference years, offering versatile applications such as examining hygrothermal behavior and energy demand in building.



Locations of observed data for simulation

Ensemble mean temperature and rainfall from bias-corrected CanRCM4-LE simulations (top), and projected changes (bottom)

Figure 2 Procedure for climate data analysis (adapted from Gaur and Lacasse (2022))

Ilomets, Kalamees, and Tariku (2019) examined the relationship between indoor conditions in dwellings and cold climate zones in Vancouver, Canada and Tallinn, Estonia, while considering various building characteristics. The research aimed to determine whether the choice between defining indoor conditions per ASHRAE Standard 160 (ASHRAE, 2016) or ISO 13788 (ISO, 2012) resulted in significantly different simulation outcomes. ASHRAE uses a simplified method, while ISO 13788 is designed based on occupancy, providing a nuanced interpretation of indoor conditions. This method was unable to reflect the actual conditions accurately because of the constant temperature. Particularly in regions with cold and damp climates, such as Vancouver and Tallinn, the use of temperature and humidity profiles based on ISO method was recommended for more ideal definitions of indoor conditions during hygrothermal simulations.

3.2. Hygrothermal performance of wood-frame wall assemblies

Wood-frame and timber wall assemblies are the common type of envelopes for residential building in North America. In order to investigate the impact of wind-driven rain on hygrothermal response of insulated wood-frame assemblies, Wang and Ge (2019) proposed a stochastic method to supplement simulations. Uncertainty arises from the extent of moisture infiltration and the location of accumulated liquids in the assemblies when precipitation enters through defects in the wall components. The results of the stochastic simulation showed a significant correlation between the location of rainwater infiltration and the degree of damage to wood-based components, with an increased risk achieved when no protective measures, such as a sheathing membrane, are in place.

Hagentoft and Johansson (2019) proposed a novel method for modelling moisture risk in wood-frame wall assemblies. A simplified numerical meta-model was developed to account for heat and mass transmission across a four-layer wall. This model can be used to investigate the probability of various performance indicators, including mould growth, heat loss, and wetness periods. Probability risk assessment was performed using the Monte Carlo approach. The results showed that an agreement between the meta-result models and simulations was an alternative to the more complicated simulation frequently used by designers. This method offers an effective way to identify moisture risk in designs while considering climate conditions.

Gullbrekken *et al.* (2019) investigated the potential consequences of increased air leakage on the moisture response of wood-frame assemblies during extreme weather. Despite commonly achieving air and vapor-tight installations through clamped joints, several defects were detected in the air and vapor barrier that can escalate air leakage. This heightened air leakage increased risk of moisture damage and reduced the energy efficiency of a building. To investigate this, experimental tests were conducted using a wall with air and vapor barriers to determine the behavior of clamped joints. The results showed that transient climate conditions tended to elevate rates of air leakage in the wall significantly. Consequently, it is important to consider concerns associated with energy consumption and the potential impact of increased air leakage caused by climate change, because clamped joints pose risk to maintaining adequate airtightness of building envelopes.

Defo and Lacasse (2021) conducted an assessment to explore the long-term effects of climate change on a cross-laminated timber (CLT) wall. The durability and moisture response of the wall in five different locations in Canada were assessed using hygrothermal simulations with DELPHIN software over 31 years. The simulations assumed a 1% wind-driven rain for moisture infiltration across all cities. The outputs compared the mould growth index on the outer layer of CLT panel between historical and future periods. The results showed a general increase in risk of mould growth in all cities, with varying proportional change. Ottawa City showed the highest growth, implying a significant shift in the mould growth index. The shift was pronounced in Ottawa, Calgary, and Winnipeg compared to Vancouver and St. John, where the initial moisture condition already posed a high risk. This suggested that the timber wall in these two cities would not resist an infiltration rate of 1% wind-driven rain.

Conroy, Mukhopadhyaya, and Wimmers (2021) used in-situ measurements and simulations to predict the future behavior of a passive house in British Columbia, Canada, under different climate scenarios. The building was characterized by its structure made of glue-laminated components and massive timber walls. Temperature and humidity sensors were strategically placed on the north and south external wall assemblies to monitor the long-term hygrothermal response. Hygrothermal models for the building were developed using WUFI software and validated with the measurement. The results showed no signs of mould onset. As yearly temperatures increased, the average relative humidity values at the sheathing board in the wall assemblies decreased, resulting in a favorable outcome.

3.3. Hygrothermal performance of wood-frame wall assemblies

Older structures, specifically those with brick or stone masonry walls, are of significant interest. This type of cladding is often subjected to retrofits to enhance energy efficiency and resistance to adverse weather conditions. When repairing masonry or historic structures, it is crucial to preserve the exterior of building facades. A common approach is to provide internal insulation to the wall assemblies. However, this retrofit activity increases risk of freeze-thaw impacts on the masonry.

Vandemeulebroucke *et al.* (2019) examined the impact of climate change on retrofitted masonry walls in a historical building in Ghent, Belgium. Using HAM models that consider heat, air, and moisture transport, the research stated the significant impact of urban heat islands and rising temperatures on the resilience of historical building envelopes. The research reported that a reduction occurred in freeze-thaw cycles in city areas, contrasting with an opposite trend in nearby rural regions. The results offered valuable insights into the distinct adaptation strategies required for masonry building in urban and rural settings.

Hagel, Sturgeon, and Cruz-Noguez (2019) focused on the problem of corrosion in steel ties typically used in European construction for connecting brick veneer to structural backing. Despite the topic being addressed in numerous research, there needs to be more understanding regarding the expected design life of these components. A time-stepped model and experimental tests estimated the corrosion rates and the corresponding remaining design lives of tie components in five different locations in Canadian cities. The prediction model results provided conservative estimates of the remaining design life of brick ties, often resulting in overestimations for ties embedded in mortar.

Hasan, Richman, and Horvat (2021) proposed an experimental method for assessing freeze–thaw damage in clay bricks using a modified frost dilatometry test. The method was used to detect the moisture content at the point of frost decay initiation, known as the saturation critical degree (Scrit). Considering the complexity of the moisture response of bricks modelled numerically and the uncertainties associated with traditional dilatometry testing, the research proposed using full-scale bricks, with micro strains along the main axes of the samples. It concluded adjustments to the conventional frost dilatometry approach were necessary to accommodate larger-sized brick specimens effectively.

3.4. Performance criteria and assessment of building envelopes

The research on the standard criteria for the assessment of hygrothermal performance of wall assemblies was addressed by Overton (2019). The investigation focused on how building modelling was used to know whether a wall system supports fungal growth or germination accumulation during service life using a variety of climate-based indicators. Gaur *et al.* (2021) focused on change in the moisture index across Canada under future climate scenarios. Moisture Index (MI) is a climate-based indicator used in the National Building Code of Canada (Canadian Commission On Building and Fire Codes, 2022) to help designers determine the acceptability of specific durability levels. The results stated that, due to global warming, the Canadian coastline and significant lake areas would experience an increase in MI. At the same time, the prairies and northern regions are expected to witness a decline in the values.

In order to determine the extent and duration of moisture retention in building components, Mukhopadhyaya *et al.* (2006) carried out research to design specific considerations for effective moisture management in exterior walls. A significant contribution was the introduction of RHT index, a unique hygrothermal response indicator designed to assess long-term moisture accumulation. The RHT index measures when heat and moisture conditions coexist during an exposure period above a given set of threshold limits. Users have the flexibility to set threshold values for temperature (T), relative humidity (RH) and exposure duration, altering them to the specific physical processes relevant to the wall materials. Higher RHT index values indicated higher severity of hygrothermal response.

Aggarwal *et al.* (2022) conducted a comprehensive examination of wood-frame wall hygrothermal responses under historical and future climate conditions using various response-based indices, including mould index (MoI), moisture content (MC16), and the RHT index. Additionally, the research aimed to compare the impact of climate inputs from various climate-based indices, such as, moisture index (MI), severity index (Isev), climate index (CI), and wind driven rain (WDR) in determining the reference year for simulations. Simulations covering a 31-year period for historical and future climate data were performed. The correlation between climate and response-based indices was evaluated using R^2 and ranking methods (RMSE and Goodness-of-fit approach). The results showed a lack of strong correlation between existing climate-based indices and the severity of weather years. Therefore, further research should develop a new, region-specific climate-based index to accurately evaluate moisture hazards.

4. **Discussions**

4.1. Overview

The impact of hygrothermal loading, particularly moisture intrusion through building envelopes, poses a significant challenge in building science, leading to the degradation of the materials and components. This degradation manifests in various ways, such as the physical deterioration of a building façade, reduced thermal resistance in wall assemblies, the potential for mould development inside the wall, and a decline in interior air quality. These consequences depict the significant impact the damage can have on the general performance of a building. The complexities of climate change and extreme weather patterns further intensify hygrothermal loads, requiring the reconsideration of building design criteria on a global scale. It is important to extend the focus to include moisture aside from thermal and energy responses in building envelope design, ensuring resilience against long-term, nonstationary climate projections.

Numerical hygrothermal models are essential for predicting the coupled heat, air, and moisture movement in building envelopes and quantifying long-term moisture performance in wall assemblies under dynamic conditions. However, applying computationally expensive 2D or 3D hygrothermal simulations over extended periods to quantify risk of moisture damage can be impractical. To address this issue, climate-based indicators or indices are commonly used for preliminary screening of climate data, identifying possible areas of excessive moisture stress on building envelopes. Although these indicators provide an estimated assessment, a more comprehensive evaluation of moisture performance in buildings requires conducting hygrothermal simulations across various periods or moisture reference years. Climate-based indicators or indices calculated over a long period can be used to indicate the severity of the moisture load for the assessment of potential risk of moisture damage at specific locations. Preliminary research has reported the importance of carefully selecting the index model because the dose-response models are derived from case-specific assemblies in certain locations. There is a need for a generic method to quantify climate risk in building envelopes accurately.

The research reviewed provided various techniques for evaluating the long-term hygrothermal performance of building materials, components, and assemblies under climate change scenarios. It thoroughly explores effective moisture control strategies, focusing on the dual importance of minimizing moisture intake into the system and maximizing the release of any moisture that enters. Several specific studies investigated ways to adapt building envelopes to climate change. These programs share a common objective, namely to ensure that components, assemblies, and construction materials show robust characteristics by posing sufficient capacity to withstand the hygrothermal loads and also sustain it over a long term through good heat-air-moisture transport management. However, a major challenge of understanding the degradation processes of building envelopes under multiple stressors and shock conditions originates from the need to combine and translate knowledge from different sources into a unified framework.

4.2. Concerns for Future Development

This review mainly examined attempts to develop reliable methods for evaluating the long-term performance of building envelopes under the influence of climate change. However, partial analyses rather than exhaustive evaluations were performed. To enhance the impact of these models, there is need to incorporate both thermal and deterioration responses within the metrics, providing a comprehensive understanding of hygrothermal behavior of building envelopes. Additional features that could improve these models include methods to determine the reduced service level of building materials, components, and assemblies considering the deterioration. The integration of potential adaptation measures and evaluation of the effectiveness in reducing risk tend to be valuable. Finally, incorporating what-if analysis to infer the estimated risk under different climate scenarios would contribute to thoroughly evaluating building envelopes performance.

While literature contributions addressed the adaptability of building envelopes to climate change and extreme events, a significant focus has been on new constructions. A gap exists in defining methods dealing with existing building assemblies, especially those open to retrofitting. Risk assessment of climate impact and adaptation, which are currently in use, tend to be mainly focused on a detailed level, including simulation of a building component, or using a qualitative approach for evaluations.

Several gaps in this current research hinder the development of an integrated decision support tool for hygrothermal performance of building envelopes, including:

- The need for development of threshold criterion for response index, e.g., RHT index, that define safe and unsafe design of envelopes system,
- Correlation between response-based (hygrothermal response) and climate-based indices (climate loads) to improve the estimates of hygrothermal responses,
- Methods to determine reference years from climate-based indices for simulation purposes aimed at minimizing uncertainties associated with future climate,
- Methods to quantify uncertainty arising from temporal behaviors of heat, air, moisture transport on assemblies, and
- Integration of climate impact in design practice into building codes and standards.

There is a lack of a comprehensive framework capable of assessing risk of specific building systems over the life cycle, considering climate change and their potential adaptation measures. To fill the identified gap, this study proposes a framework of high-level risk assessment for building components performance considering climate change. For a framework to improve the decision-making process, some criteria it shall possess include: (1) transparent, easy to communicate between stakeholders, (2) quantifiable, and (3) based on best available knowledge, techniques and data.

The proposed framework is designed to quantify the impact and effectiveness of potential adaptation measures of building envelopes under different climate scenarios. Figure 3 shows how the framework would achieve this objective. The first part is a risk assessment where the hazard-component interactions are quantified. This part investigates the relevant factors and the interdependencies between factors in hazard-component interaction for the given climate scenarios. The second part is a decision support where risk prioritization is performed. This part generates prioritization rankings that consider climate scenarios, building component severity, and uncertainty related to hazard-component interactions for each time horizon. To reduce possible hazards and/or consequences, resilience measures are selected as the enablers of risk mitigation. In the measure selection, there is a need to incorporate low-carbon options whenever possible.

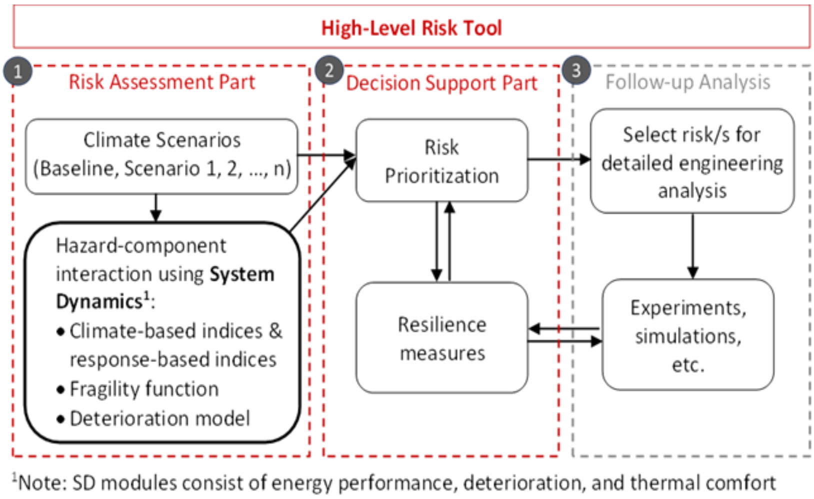
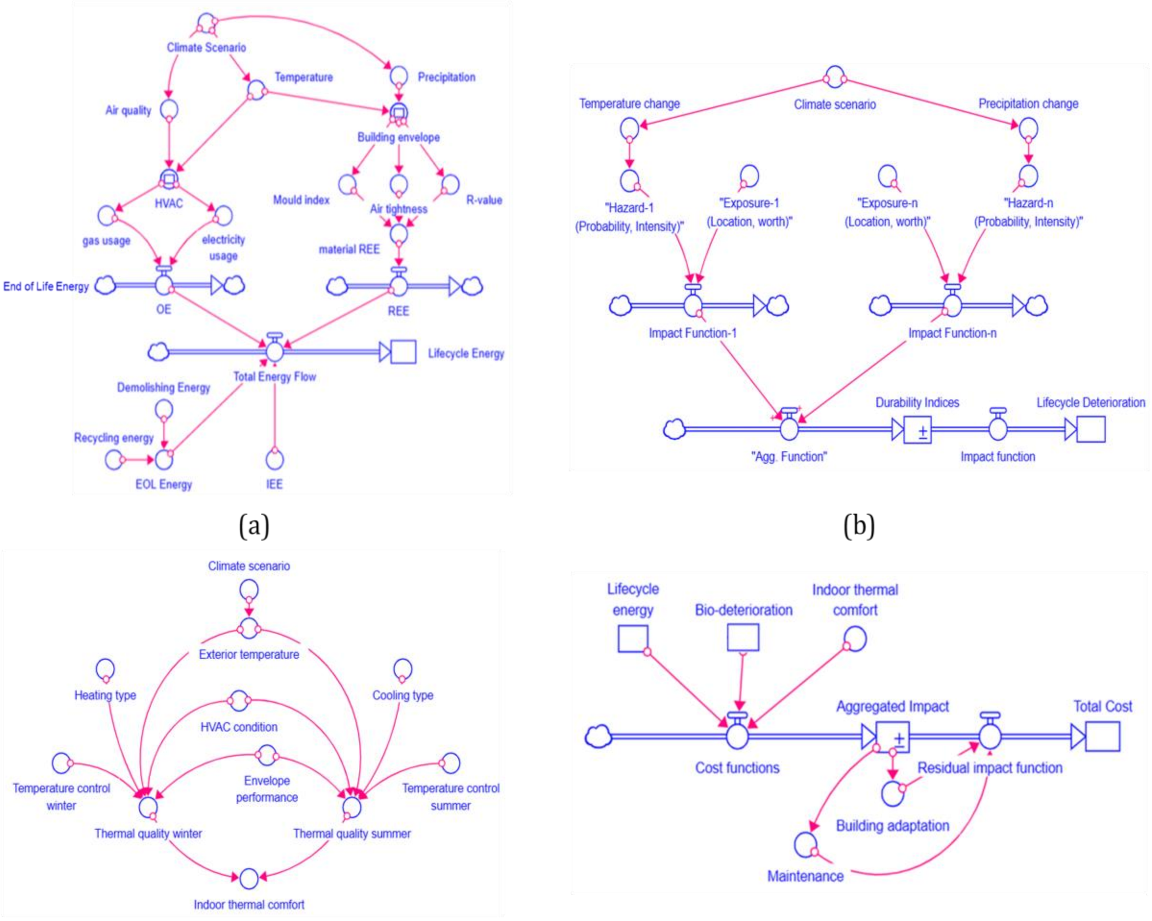


Figure 3 The proposed conceptual framework of climate risk assessment

The third part is follow-up analysis where detailed engineering analysis of the largest risks is performed. This part can be supported by laboratory experiments, building simulations, or field measurements to specifically investigate and validate the risks and the associated resilience measures. The framework supports decision-making with flexibility, allowing for numerous component-level impact assessments and exploration of various feasible resilience options before zeroing in on the most promising ones.

System dynamics (SD) are used in the hazard component interaction part of the risk assessment to quantify the potential impact of climate change and internal characteristics on the degradation process of building envelopes. System dynamics is a modelling approach based on feedback systems theory, capable of identifying behavioral patterns of complex systems by quantifying interactions and develops a time-dependent process. The model is equipped with a causal map, which allows the user to visually investigate the relevant factors and the dependencies among factors. Hazard-component interactions can be defined either based on the established indices, fragility functions, or deterioration models. The SD part is designed to capture three major performance aspects of building envelope: (a) energy performance; (b) biodeterioration; and (c) thermal comfort.



(a) (b)

(c) (d)

Note: IEE: Initial Embodied Energy
OE: Operational Energy
REE: Recurrent Embodied Energy
EOL: End of Life Energy

Figure 4 System dynamics models for climate risk assessment: (a) energy lifecycle, (b) bio-deterioration, (c) thermal comfort, and (d) total component performance

The system dynamics model of the proposed framework is shown in Figure 4. An example of the simulation is visually represented through a causal map of the energy part in Figure 4a. The model depicts the temporal change and incorporates various hazardous risks to relevant assets. In a typical simulation of the model, IEE is computed and applied during the design phase of building, serving as the starting value for the life cycle energy stock. As the simulation progresses into the usage phase, OE and REE are calculated. The OE section of the model simulates gas and electricity use over the building lifetime, while the material maintenance and replacement schedules influence REE. The EOL section covers both the energy required to demolish the structure and the energy returned to the grid by recycling the materials, depicted as balanced feedback loop. In the simulation, all energy requirements are aggregated into the life cycle energy stock, providing a comprehensive overview of the energy requirements of building across the entire life cycle at the end of one simulation period.

In the biodeterioration cycle, as shown in Figure 4b, a causal map depicts how components undergo temporal change and face associated risk from hazards and damages. To characterize damage, an impact function is initially applied to a specific asset type, including the computation of exposure (asset value) and hazard classes (probability of occurrence, intensity, and location) at a given time. Figure 4c depicts the model for indoor thermal comfort. Due to subjectivity of occupant perception, this part is designed as average comfort level based on survey from occupants, and hence no accumulation stock modelled in the model. Outputs from the three parts are aggregated in monetary value as depicted in Figure 4d to produce total component performance. The adaptions are computed as the simulation progresses to ascertain the benefits and residual risk of these interventions.

5. Conclusions

In conclusion, the effective control of heat, air, and moisture transfer in building envelopes under climate conditions is crucial to ensure an acceptable performance and service life. The increasing risk posed by climate change on building envelopes and the awareness of the need to include climate resilience in the design of critical components led to investigations to improve the understanding of this process. Various models and methods were developed to characterize hygrothermal responses and associated risk. Despite these advancements, there remains a significant gap in integrating the research outcomes into a comprehensive, risk-based decision support system that considered climate-change scenarios and building design. In this investigation, a comprehensive review was undertaken to examine previous research efforts to enhance the characterization of hygrothermal performance in building envelopes across four major sectors based on content analysis. An innovative approach based on system dynamics, a structured and integrative tool capable of explicitly capturing factors influencing building performance over time under the impact of climate change, was proposed to address the existing gaps. The developed model incorporated both thermal and biodeterioration responses into the metric. It enables the identification of climate impacts on building systems and an improved comprehension of desirable hygrothermal responses through adaptive measures. Future work can examining implementing this framework and applying it to real building cases to test the viability of the model as a risk assessment tool.

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