Developing a design framework for climate responsive façades: Material selection and performance metric identification

Shahrzad Soudian, Ph.D Candidate, Ryerson University
Umberto Berardi, Associate Professor, Ryerson University
shahrzad.soudian@ryerson.ca
(905) (923) - (2911)
350 Victoria st.
Toronto, ON M5B 2K3

Abstract

The increasing trend of energy efficient building design is directly linked with the adverse impacts of buildings on the environment, in addition to the implications posed by climate change-related events on the resiliency of buildings. The move towards energy efficient building design has often been characterized by targeting comfort related energy conservation methods. Addressing building energy demands to provide indoor environmental comfort is a key factor considering the large share of space heating, cooling, and ventilation energy use. Particularly, optimizing the performance of the building envelope as the main interface between the outdoor and indoor environments has been a major focus for energy saving strategies in buildings. However, a new paradigm in energy efficient and resilient building design is needed to address the current energy and climate challenges. Climate responsive building envelopes present a considerable potential in this area to address comfort and energy demands in buildings through dynamic and adaptive performance. This is in contrast to the traditional approach of building envelope design that envisioned the envelope as a static barrier and shield to environmental loads. In this research, the design phase of an opaque climate responsive façade (CRF) module is investigated for the climate context of Toronto, Canada. The multi-functional façade module is proposed to dynamically regulate the flow of heat, air, and moisture into buildings. A primary design framework was proposed with to systematically compare alternative materials and systems. For this purpose, several response parameters are defined, namely the purpose of each module, objectives, response functions, and adaptation strategies. Furthermore, metrics and key performance indicators related to the responsiveness of the module were discussed. After the decomposition of several alternative materials and systems using the framework into response parameters, several CRF scenarios were configured. A matrix of design range and system range values have been defined for each scenario based on the performance metrics. This design framework provides the foundation for selection and performance evaluation of a CRF. The results of this study could lead to a generalized approach for informed decision-making and design prediction for transient responsive façade design with the potential to turn design concepts into engineering solutions.

1. Introduction

Energy efficient and sustainable building design have often focused on enhancing the performance of the building envelope, particularly the building facade as a critical element for building performance. The boundary created by the building façade determines the indoor environmental quality (IEQ) in building spaces. The properties and configuration of the building façade determine the magnitude of change in indoor environments based on the outdoor boundary condition variations. Nevertheless, the focus of conventional building facades has been on static performance, disregarding the transient nature of environmental fields surrounding the façade (Addington 2015). This has resulted in decoupling the indoor spaces from the outdoor microclimate, and thus increasing the demand for mechanical conditioning.

This high reliance on mechanical space conditioning has entailed high energy use and greenhouse gas emissions attributed to buildings (Ascione 2017; Berardi 2017). Furthermore, the implications of climate change on the built environment could critically threaten the resiliency of buildings as a result of changing weather patterns.

To balance the three fundamental aspects of occupants, environment, and buildings, transiency in building façade performance to regulate and translate the flow of energy and mass into and out of the building must be considered. This could be achieved by adopting dynamic and adaptive façade systems that respond to different boundary conditions by changing their properties in a reversible manner (Casini 2016). Thus, the performance of the building facades, depending on their overall functionality determines the rate in which the outdoor conditions are translated into the interior building environment. The term climate responsive façade (CRF) encompasses a wide characterization of dynamic facade systems. The terminology of dynamic façades includes different terms such as adaptive, intelligent, smart, switchable, interactive, alive, active, etc. that have been interchangeably used in the literature (Loonen et al. 2013; Looman 2017). CRFs are defined as building façades that could repeatedly and reversibly respond to changing boundary conditions to introduce natural energy sources into buildings to improve the overall performance of buildings.

1.1. Background

There has been a growing interest in the design and application of CRFs. The need for a new paradigm in high-performance building façade design has been emphasized in the literature mainly to satisfy the increasing comfort demands, respond to the changing climate conditions as well as rigorous legislations for energy efficient building design. CRFs are in contrast to climate indifferent or climate combative façade design primarily designed as barriers and shields to environmental loads (Perino and Serra 2015; Attia et al. 2018). CRFs act as filters in regulating the different environmental loads such as light, heat, air, and moisture into and out of the building. Another limitation of static facades, particularly the new generation of high-performance facades is the risk of competing parameters that could hinder their intended performance (Taveres-cachat et al. 2019). Responsive facades could address both indoor environmental comfort and energy savings objectives (Loonen et al. 2013).

The purpose to apply CRFs can range from single objectives such as regulation of daylight, airflow, or heat transfer, to multiple objectives through simultaneous regulation of several loads. Examples of responsive façade systems include dynamic shading systems, smart glazing, smart materials, and dynamic insulation materials. Improving the indoor environment in buildings has often been prioritized over energy saving goals in the design of CRFs (Perino and Serra 2015; Kosir 2016). Indoor environmental comfort delivery in CRFs is directly connected to the dynamics of the outdoor local microclimate rather than standard design criteria based on macroclimate considerations. By reviewing the literature on existing CRFs through different databases and built examples it was observed that the two main objectives addressed in CRFs were regulating the solar and thermal energy transfer through the transparent and opaque parts of the façade in buildings. However, a limited number of studies have focused on the regulation of airflow and moisture transfer in CRF design to improve IEQ.

Through an investigation on the different concepts of changeability and responsiveness in facades, it was argued that both changeability and robustness in the façade performance must be met. Yet considering the conflicting nature of change and robustness, such conflicts could be resolved by introducing different levels or components in a system to meet each aspect, in other words creating a multi-functional system (Perino and Serra 2015). In the area of multi-functional

CRFs, two main technical approaches have been observed. The first is to introduce several functionalities in a CRF by combining different layers of dynamic performing materials and systems. The ACTRESS (ACTive, RESponsive and Solar) façade prototype including an opaque, and a transparent module was designed to provide passive and active thermal energy storage, optimized thermal insulation and thermal inertia properties, and a heat recovery system to preheat the ventilation air in different materials and layers (Favoino et al. 2014). The second approach for multi-functional CRF design is to introduce multiple response functions in a single layer or material. Craig and Grinham (2017), developed multi-functional materials using millimeter-scale pores to temper the incoming air in a single panel as heat exchangers instead of insulators with multiple layers.

The multitude of interactions between different systems and environments that need to occur in a CRF requires a comprehensive design approach different from normative façade design processes to take into account all the different variables for the systems. This is particularly important for the selection of technologies and mechanisms that can effectively fulfill the intended objectives. A lack of research in the initial design of CRFs has been indicated, particularly on systematic selection methodologies to consider different responsive mechanism rather than absolute performance. It has been argued that for the design of CRFs, focusing on the process of change in different technology alternatives is a better approach. Extracting and breaking down the properties and objectives of responsive technologies was indicated as a necessary step to have a portfolio of solutions (Attia et al. 2018; Taveres-cachat et al., 2019).

This research aims to create a design framework as a basis for material and system selection for an opaque CRF module to be integrated in the climate context of Toronto, Canada. Particularly, the objective of this study is to provide a design path to develop a multi-functional CRF module with the potential to regulate the flow of heat, air, and moisture in a monolithic layer. Furthermore, the metrics required for the performance evaluation of this module are investigated to assist in the decision-making process in addition to the initial framework. This paper is part of a larger study that investigates the design, development, and performance evaluation of a transparent, and an opaque CRF module for IEQ improvements in buildings.

2. Methodology

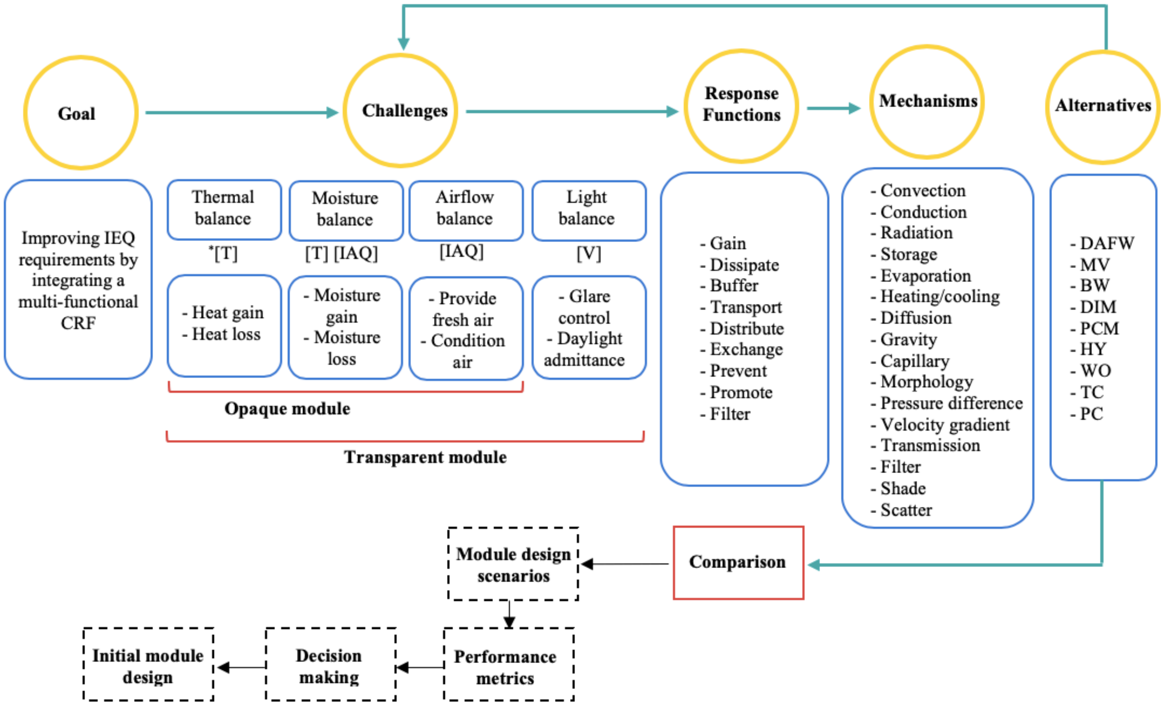
2.1. Design framework

The first step to designing the multi-functional CRF (MF-CRF) is to define the conceptual theories to connect the objective of the façade to appropriate technological solutions. A design framework is created to categorize different technologies and mechanisms based on specific response parameters. Considering the large body of technologies available to design a CRF, the design framework presented in this study is focused on specific systems and material alternatives to compare their functionality to be selected/combined for the CRF module. The alternatives compared in this study for an opaque MF-CRF are listed in Table 1.

The alternatives were selected primarily based on the extent of their responsiveness, applicability to buildings as individual components as well as in combination with other responsive elements. To design the MF-CRF, the alternatives must either present multi-functional responsiveness individually or be combined with other building systems or materials to perform multiple functions. The approach to creating the design framework is shown in Fig. 1.

Table 1. System and material alternatives

Alternatives	Function / Application	References
Dynamic insulation material (DIM)	The wall acts as a heat exchanger in relation to the flowing air. The airflow path and the direction of the heat flow could be the same or opposite which determines the U-value of the insulation as a function of air flow rate.	Imbabi et al. (2012)
Phase change materials (PCM)	PCMs store heat by undergoing a phase change at specific melting temperatures. Heat is stored during the melting phase and discharged when temperatures go down by solidification. PCMs can be integrated in porous materials or separate containers based on encapsulation.	Favoino et al. (2014)
Hydrogel (HY)	Superabsorbent polymers that can absorb water by 90% of their weight. At higher moisture levels the gel absorbs excess moisture and with higher temperature and lower moisture content, the gel discharges the stored water. Hydrogel can be applied as separate panels or be integrated into ceramics or concrete.	Rotzetter et al. (2012)
Wood (WO)	Various types of wood products in buildings such as timber structure, and plywood panels have moisture buffering capabilities. This hygroscopic behavior of wooden materials allows them to absorb, store, and release moisture to naturally regulate humidity variations in spaces.	Zhang et al. (2017)
Breathing walls (BW)	The system uses porous air permeable building materials that act as heat exchangers. The movement of the air from outside to inside is controlled through pressure balance, and the incoming fresh air is pre-heated or pre-cooled through conduction heat transfer from interior exhaust air.	Craig and Grinham (2017)
Milli-fluidic/ Vasculature networks (MV)	Vascular or fluidic networks that transport various fluids and can be made using elastomeric layers to be attached to different surfaces. A heat exchange capability is achieved to additionally heat or cool the fluid inside the networks.	Craig and Grinham (2017) Hatton et al. (2013)



*[T]: Thermal comfort - [IAQ]: Indoor air quality – [V]: Visual comfort

Figure 1. Process of decomposing the alternatives in the design framework for a MF-CRF module

The response functions used to categorize the alternatives in the design framework are as follows:

- **Change mechanism:** The process the CRF undergoes to change from its initial state to the intended state;
- **Stimulus:** The trigger that initiates the change;

- **Scale of response:** The scale of the applied CRF concept, classified into material [Mat.], component [Comp.], system [Syst.], and façade [Fac.] (system refers to a mechanism that can be embedded into a component)- Micro-scale [Mic.], Macro-scale [Mac.]
- **Objectives:** The main purpose to apply the CRF: Thermal comfort [T], Visual comfort [V], Indoor air quality [IAQ];
- **Technologies:** Description of the technologies used to perform the response;
- **Control:** Type of control [Intrinsic (Intr.); Extrinsic (Extr.)];
- **Time scale of change:** The temporal scale for the response function categorized into real-time [Minutes and Seconds], hourly, daily, and seasonal (Seas.);
- **Building integration:** The architectural integration of the technology to buildings including the entire façade, or within a component of the façade. New [New] and retrofit [Ret.] application of the technology is also shown.

Based on the design framework different alternative scenarios could be generated by combining the alternatives indicated in Table 1.

2.2. Performance metrics

To assess the functionality of the CRF module and its applicability to buildings, the first step is to understand on what basis and criteria should the performance of a CRF be assessed. Table 2 summarizes the design criteria and sub-criteria required for an opaque CRF module. Key performance indicators and performance metrics appropriate for dynamic facades have been reviewed and based on the selected alternatives, and the criteria from Table 2, a framework for appropriate metrics will be generated in this study. Performance metrics are defined for each sub-criterion to show how the performance of the MF-CRF should be quantified.

Table 2. Design criteria for the opaque CRF module.

Main criteria	Sub criteria	Definition
C1: Environmental	SC11: Outdoor boundary Conditions SC12: Indoor boundary conditions	The outdoor boundary conditions in this study are defined based on the climate context of the city of Toronto, in Canada; The indoor boundary conditions can be based on a specific type of building
C2: IEQ	SC21: Thermal comfort SC22: Indoor air quality (IAQ)	ASHRAE Standard 55 (ASHRAE 2017) ASHRAE Standard 62.1 (ASHRAE 2016)
C3: Technical	SC31: Change mechanism SC32: Changeability SC33: Robustness SC34: Durability SC35: Flexibility SC36: System configuration	Various change mechanisms to achieve the intended goal; Responsiveness of the module to environmental loads; Ability to adapt, different temporal scales; Physical durability as well as stability of responsive behavior; Flexible performance under uncertainty or for a wider design range; The layout, and positioning of the materials and systems in a monolithic module;
C4: Architectural	SC41: Compatibility SC42: Applicability	Compatibility of the module to typical façade construction approaches; The module must be applicable to both new and retrofit construction;

By determining the criteria, and the performance metrics, performance quantification of a CRF module can be done by measuring the design range and the system range for the alternative scenarios. Figure 2 shows the process that must be performed for each scenario to quantify its performance prior to initial selection using decision-making methods. Finally, an example of an alternative scenario will be presented and broken down based on Fig. 2 to represent the framework and processes introduced in this study by defining the system and design range.

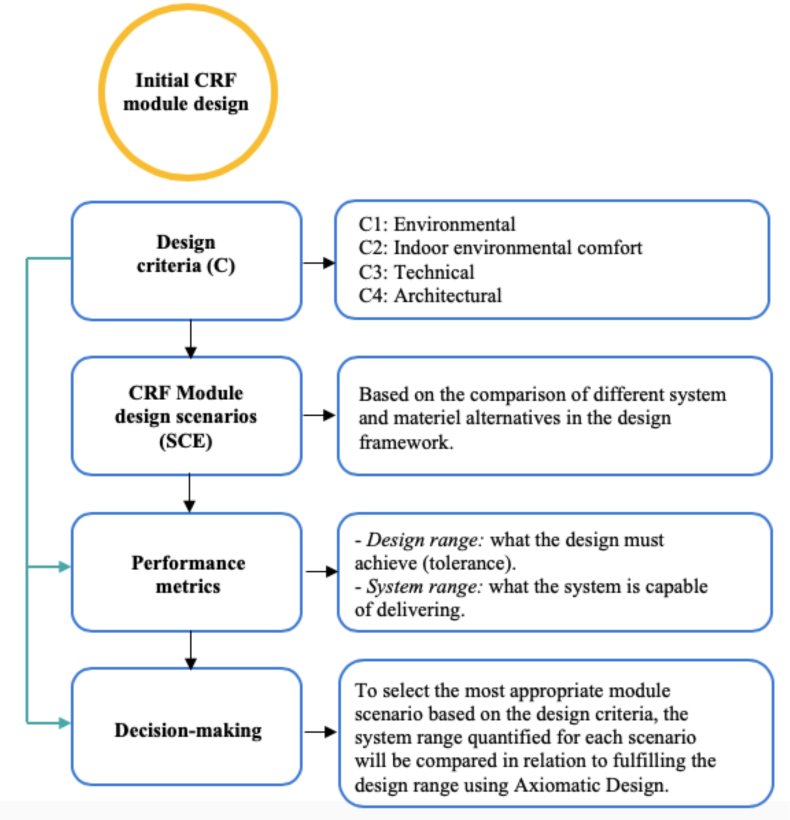


Figure 2. Process of initial CRF module design based on alternative scenarios

3. Results

3.1. Design framework

The process of creating the framework shown in Fig. 1 was implemented for each alternative individually. The overarching goal was first divided into IEQ challenges that must be met. For each challenge, two groups of objectives must be achieved to maintain the balance. The next step includes the response functions which are simply a decomposition of the objective groups. Similarly, the response functions are further broken down into physical and thermodynamic actions that execute the response functions. Each alternative is then reviewed through this process and decomposed accordingly to understand its functionality, design, and configuration. Table 3 shows the framework created for the opaque CRF module.

As the framework shows, each alternative undergoes different mechanisms to achieve the objective of thermal, moisture, and airflow balance. A further expansion of the framework could indicate the stimulus, control, and time scale specifically for each one of the mechanisms. However, this could be challenging considering incomplete information in the data gathering phase. All the alternative cases in the framework can be integrated into both new and retrofit construction. However, for retrofit integration of the majority of alternatives, complete removal and replacement of the existing façade components are required. The application of this framework can be generalized based on different alternative materials and systems that can be broken down into response parameters to create different design scenarios.

Table 3. Design framework for the opaque MF-CRF module.

Alternative	Response function	Mechanism	Stimulus	Control	Time scale	Response Scale	Technology	Architectural integration
DIM [T] [IAQ]	Gain Dissipate Filter	Convection	Temperature Airflow rate	Ext. (Active mode) Intr. (Passive mode	Real-time Seasonal	Comp. Mac.	Thermal conductivity can be controlled within a desirable range. Porous and air permeable materials are used to filter the air.	Complete component of the DIM replacing the typical insulation layer [New] - [Ret.]
		Conduction						
		Heating/cooling						
	Transport Exchange	Pressure difference						
		Counter-current flow						
		Velocity gradient						
PCM [T]	Buffer	Storage	Temperature	Intr.	Daily Seasonal	Mat. Mic.	Organic, inorganic PCMs that undergo solid -liquid phase change at specific melting ranges to store thermal energy.	Integrated in micro or macro-encapsulated systems [New]- [Ret.]
		Heat radiation						
HY [T] [IAQ]	Buffer	Storage	RH Temperature	Intr.	Daily	Mat. Mic.	A smart super absorbent gel consisting of an insoluble polymer matrix that swell up to store water. At lower humidity levels, water is discharged.	Applied as a coating layer that can be integrated as a layer in the façade [New]- [Ret.]
		Retention						
WO [T]	Buffer	Heat storage	Temperature RH	Intr.	Daily	Mat. Mic.	The ability to absorb, store and release moisture due to hygroscopicity that regulates humidity variations. Moisture storage in wood also leads to thermal storage.	Applied as a single layer with different thicknesses in the façade [New]- [Ret.]
		Moisture storage						
		Moisture retention						
	Transport Distribute	Capillary transport						
		Diffusion transport						
		Morphology transport						
BW [T] [IAQ]	Gain Dissipate	Convection	Temperature Airflow rate	Extr. (Fans) Intr. (Pressure equalized rainscreen)	Real-time Seasonal	Mat. Comp. Mic. Mac.	Either porous fiber panels or using materials with geometrically made pores to allow for the flow and conditioning of air.	Applied in a single layer in various building materials [New]- [Ret.]
		Conduction						
	Exchange	Counter-current flow						
	Transport	Pressure difference						
		Diffusion transport						
MV [T] [IAQ]	Gain Dissipate Filter	Convection	Solar Temperature RH Airflow rate	Extr. Intr.	Real-time Daily	Syst. Mac.	Flow of fluids inside millimeter sized channels that can distribute the fluid into different sections. Depending on the application and the type of fluid the functionality of this system varies.	Constructed using polymer elastomers attached to building surfaces. [New]- [Ret.]
		Conduction						
		Heating/cooling						
	Buffer	Heat storage						
		Moisture storage						
	Transport Distribute	Pressure difference						

Table 4. Functional comparison chart- Opaque CRF module

Functions (IEQ)	**Thermal balance**		**Moisture balance**		**Airflow balance**	
Processes	**Gain**	**Loss**	**Gain**	**Loss**	**Fresh air**	**Condition air**
Energy loads	Heating	Cooling	Ventilation	Heating/cooling	Ventilation	Pre-heating/cooling
DIM	+	+	-	-	+	+
PCM	+	+	-	-	-	-
HY	-	-	+	+	-	-
WO	+	+	+	+	-	-
BW	+	+	-	-	+	+
MV	+	+	+	+	+	+

In the case of an opaque MF-CRF module, the simultaneous control of moisture, heat, and airflow is required. A functional convergence was generated from the framework inspired by an approach used by Badarnah (2017) to indicate the multi-functionality of each system shown in Table 4. The table assesses the alternatives that can be complemented to design a module. A cross combination of environmental factors and the response parameters between alternatives would generate different initial design scenarios.

3.2. Performance metrics and initial design

From the results of the design framework shown in Section 3.1 and the design criteria identified in Table 2 five design scenarios (SCE) are generated for the opaque MF-CRF module as shown in Table 5. These scenarios are made by combining different mechanisms from the alternatives. The combination of the alternatives was in consideration of the response parameters, particularly, the stimulus, control, time scale, and response scale. It must be noted that the design of the opaque CRF module is considered as a rainscreen system, thus the scenarios presented in Table 5 are located behind the rainscreen. The interior finish panels are also considered to be installed with a gap to the actual module to allow for airflow.

Table 5. Design scenarios generated from the alternatives for the opaque MF-CRF module.

Scenario	**Alternatives**	**Description**
SCE 1	BW + MV + PCM + WO	Breathing wall (wood substrate) with millimeter channels coupled with 2 MV channels, one filled with water which is circulated with pump at different temperatures, and one filled with a PCM.
SCE 2	DIM + HY + PCM	Dynamic insulation system with rockwool coupled with a hydrogel panel and a PCM macro-encapsulated panel.
SCE 3	DIM + MV + PCM	Dynamic insulation system with rockwool coupled with a wooden panel. Two MV channels are attached to the front and back of the wood panel, one filled with water, and one filled with PCM.
SCE4	BW + MV + WO	Breathing wall (Wood substrate) with millimeter channels coupled with 2 MV channels. One for heating, and one for cooling, filled with water.
SCE 5	DIM + BW + MV + WO	Dynamic insulation material attached to a breathing wall (wood substrate) with two MV channels for heating and cooling (water filled).

The performance metrics for the opaque CRF module are determined using the system range and the design range values in consideration of Table 2. The design range for the CRF is identified based on the C1 and C2, while the system range is determined by considering C3 and the specific parameters for the alternatives investigated in this study. Table 5 shows the performance metrics for the design of an opaque CRF module that mainly concerns the environment and room boundary conditions surrounding the CRF. The system range is used to calculate the balance equations showing the component scale performance of the CRF to allow for comparison or optimization of the selected scenarios. The performance metrics shown in Table 7 are in consideration of the technical criteria (C3). SC36 and the architectural criteria (C4) would be assessed in the final design and optimization phase of the CRF module.

Table 6. Design range parameters required for the analysis of an opaque CRF module.

Sub-criteria	Design range parameter	Variables
SC11	Thermal conditions Outdoor air quality	Mean daily outdoor temperature ($t_{mda(out)}$) Solar radiation intensity Humidity Contaminant concentration (%)
SC12	Thermal design Indoor air quality	Indoor air temperature (t) Mean radiant temperature Contaminant concentration requirements for the building type
SC21	Predicted mean vote (PMV) and Standard effective temperature (SET) model Temporal variation	Air velocity (V_a) Indoor air temperature (t) Humidity (RH) Mean radiant temperature (t_r) Operative temperature (t_o) Radiant temperature asymmetry Temperature fluctuations with time (t, t_r)
SC22	Ventilation rate procedure IAQ procedure	Outdoor air variable intake flow (V_{ot}) Outdoor air treatments Zone air distribution effectiveness (V_{oz}) Contaminant concentration levels (%)

Table 7. Performance metrics for the design of an opaque CRF module

Alternative	System range	Performance metric	References
DIM	Dynamic U-value Airflow velocity Porosity of the insulation Thickness Pressure difference Inlet/outlet temperature	Dynamic insulation efficiency Pre-heating efficiency (Heat recovery) System ventilation efficiency (E_v) Total heat efficiency of the system Solar heat gain efficiency Air filtration efficiency Reversibility	Bianco et al. (2018) ASHRAE (2016) Imbabi (2012)
PCM	Latent heat capacity Melting temperature range Specific heat capacity	Thermal buffer efficiency Heat storage/discharge efficiency Solar heat gain efficiency Area heat storage capacity Cycle stability	Bianco et al. (2018)
HY	Moisture effusivity Thickness Weight Water vapor permeability Moisture capacity	Moisture buffer value (MBV) Water content Moisture uptake/release Cycle stability	Zhang et al. (2017)
WO	Porosity Specific heat capacity Moisture diffusivity Moisture effusivity Water vapor permeability Moisture capacity	MBV Moisture uptake/release Cycle stability	Zhang et al. (2017)
BW	Thermal conductivity Thickness Number and diameter of air channels Pressure difference Inlet/outlet temperature	Moisture penetration depth Moisture diffusivity Pressure drops Air filtration efficiency Reversibility Heat recovery efficiency System ventilation efficiency	Craig and Grinham, (2017) Hatton et al. (2013) Imbabi (2012)
MV	Channel diameter Distribution network (geometry) Inlet/outlet temperature Inlet/outlet moisture content Flow rate Pressure difference	Temperature profiles Effectiveness of heating/cooling Heat exchange efficiency	Hatton et al. (2013) Craig and Grinham (2017)

3.3. Application of the frameworks to a CRF scenario

To better illustrate the application of the frameworks presented in this study to design the MF-CRF, the design of the SCE 1 is explained. Figure 3 shows a schematic design for SCE 1 comprised of a breathing wall which is a wood panel with air holes, two milli-fluidic panels, one for heat buffering using PCMs, and one for additional conditioning of air using water-filled channels with different temperatures. Fig. 4 shows the design process of the module.

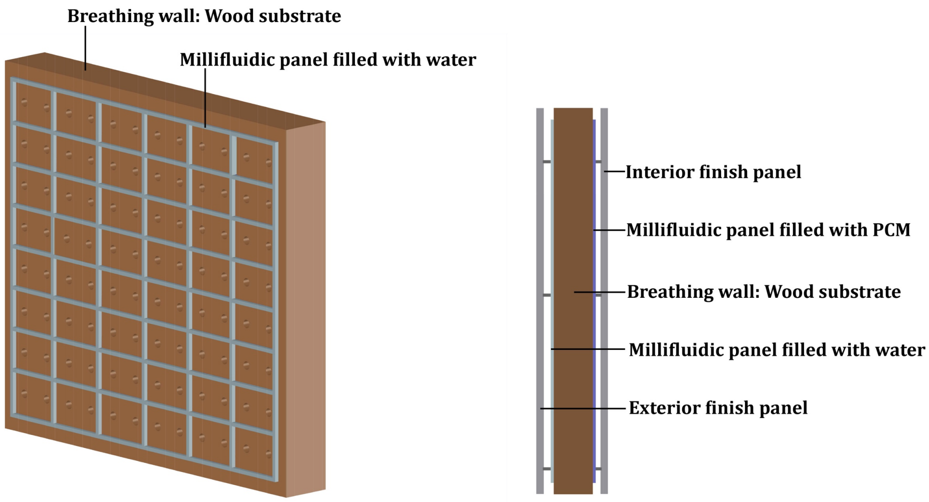
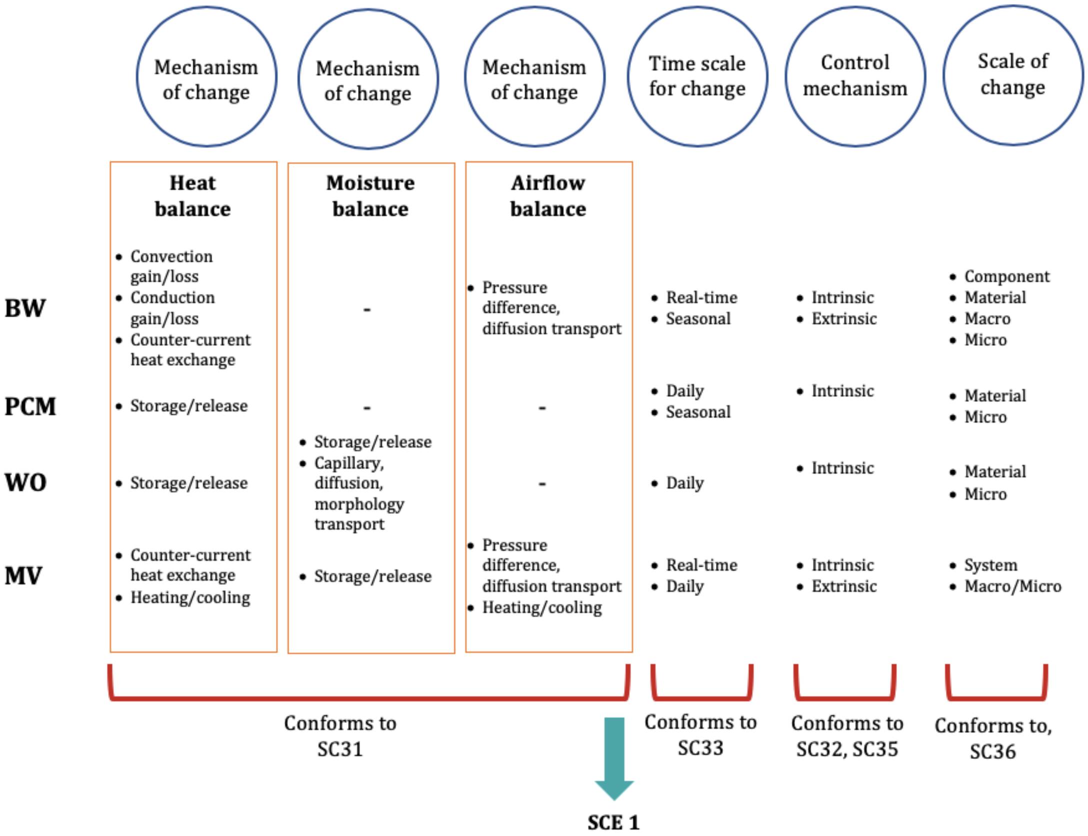


Figure 3. Schematic design of SCE 1 for the opaque MF-CRF



	Mechanism of change Heat balance	Mechanism of change Moisture balance	Mechanism of change Airflow balance	Time scale for change	Control mechanism	Scale of change
BW	• Convection gain/loss • Conduction gain/loss • Counter-current heat exchange	-	• Pressure difference, diffusion transport	• Real-time • Seasonal	• Intrinsic • Extrinsic	• Component • Material • Macro • Micro
PCM	• Storage/release	-	-	• Daily • Seasonal	• Intrinsic	• Material • Micro
WO	• Storage/release	• Storage/release • Capillary, diffusion, morphology transport	-	• Daily	• Intrinsic	• Material • Micro
MV	• Counter-current heat exchange • Heating/cooling	• Storage/release	• Pressure difference, diffusion transport • Heating/cooling	• Real-time • Daily	• Intrinsic • Extrinsic	• System • Macro/Micro

Figure 4. Diagram for the alternative scenario generation.

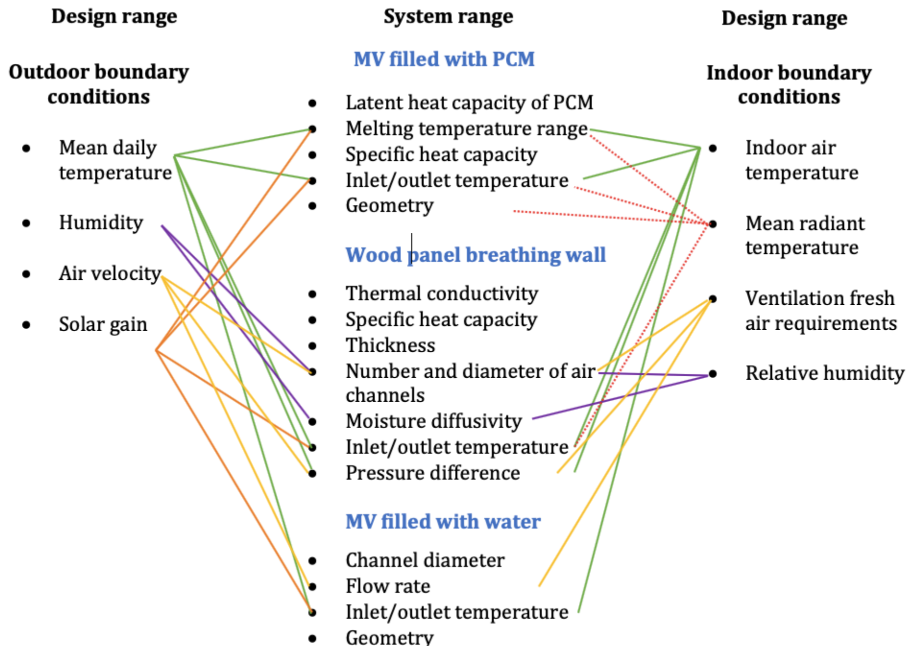


Figure 5. Design range and system range parameters for SCE1.

The scenario must fulfill the initial goals of thermal, moisture, and airflow balance through the use of different alternatives. First, from Table 4 the primary response functions for each alternative is observed, showing that all the alternatives regulate the flow of heat. BW and MV could also regulate and condition airflow, while the wood panel can effectively target moisture regulation. The second step is shown in the diagram in Fig. 5 to evaluate if the design criteria defined in Table 6 could be relatively met in this scenario based on the response parameters of each alternative. Finally, the impact of specific design range values on the specific system range values are presented. The alternative scenarios shown in Table 5 achieve the IEQ goals in different ways. The process in Fig. 4 and Fig. 5 are repeated for all the scenarios to have a similar context for comparison. By characterizing the system ranges, and their relation to the design range, the C2 comfort requirements can be predicted for each scenario in the climate context of Toronto.

Finally, the performance metrics for the SCE1 module can be determined from Table 7 for thermal balance, moisture balance, and airflow balance by combining the metrics defined for each system. The outcome of this design, and the performance metric identification leads to an initial design for this scenario. After the final decision-making to select the best performing alternative scenario (Fig. 2), the final design of the selected opaque MF-CRF will be optimized further considering different variables, material properties and configurations.

4. Conclusions

The development of a design framework for an opaque CRF module was presented. The framework acts as a primary step for the selection of appropriate technologies, and response parameters for the CRF module to fulfill IEQ goals. The framework can be translated into decision-making algorithms to combine and select the appropriate choice of alternatives to design a CRF. This could lead to a generalized approach for informed decision-making and design prediction for responsive façades. This design decision approach is in contrast to the typical process of new façade design involving time-consuming and costly initial research and development by trial and error. The performance metrics categorized in this study could be characterized for a specific design range to quantify the system range of alternative scenarios. This also provides a basis for material comparison and decision-making.

Future research in this study applies the same framework for alternative scenario definition for a transparent CRF module. Subsequently, the defined system range and design range values (Toronto climate) for the CRF modules will be applied to Axiomatic Design method to select the appropriate scenario based on a weighted fuzzy approach.

References

Addington, Michelle D. 2015. “Smart Architecture, Dumb Buildings.” In *Building Dynamics: Exploring Architecture of Change*, edited by B Kolarevic and V Parlac, 60–68. New York: Routledge.

Ascione, Fabrizio. 2017. “Energy Conservation and Renewable Technologies for Buildings to Face the Impact of the Climate Change and Minimize the Use of Cooling.” *Solar Energy* 154: 34–100.

ASHRAE. 2017. “ANSI/ASHRAE Standard 55-2017: Thermal Environmental Conditions for Human Occupancy.”*https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy*

ASHRAE. 2016.” ANSI/ASHRAE Standard 62.2-2016: Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings.” https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2

Attia, Shady, Senem Bilir, Taha Safy, Christian Struck, Roel Loonen, and Francesco Goia. 2018. “Current Trends and Future Challenges in the Performance Assessment of Adaptive Façade Systems.” *Energy & Buildings* 179: 165–82.

Badarnah, Lidia. 2017. “Form Follows Environment: Biomimetic Approaches to Building Envelope Design for Environmental Adaptation.” *Buildings* 7 (4): 40.

Berardi, Umberto. 2017. “A Cross-Country Comparison of the Building Energy Consumptions and Their Trends.” *Resources, Conservation and Recycling* 123: 230–41.

Bianco, Lorenza, Ylenia Cascone, Stefano Avesani, Pascal Vullo, Timea Bejat, Roel Loonen, Stefan Koenders, Francesco Goia, Valentina Serra, and Fabio Favoino. 2018. “Towards New Metrics for the Characterisation of the Dynamic Performance of Adaptive Façade Systems.” *Journal of Facade Design & Engineering Volume* 6.

Casini, Marco. 2016. “Designing the Third Millennium’s Buildings.” In *Smart Buildings*, 3–54. Woodhead Publishing.

Craig, Salmaan, David Harrison, Andrew Cripps, and Daniel Knott. 2008. “BioTRIZ Suggests Radiative Cooling of Buildings Can Be Done Passively by Changing the Structure of Roof Insulation to Let Longwave Infrared Pass.” *Journal of Bionic Engineering* 5 (1): 55–66.

Favoino, Fabio, Francesco Goia, Marco Perino, and Valentina Serra. 2014. “Experimental Assessment of the Energy Performance of an Advanced Responsive Multifunctional Facade Module.” *Energy and Buildings* 68 (PART B): 647–59.

Hatton, Benjamin D., Ian Wheeldon, Matthew J. Hancock, Mathias Kolle, Joanna Aizenberg, and Donald E. Ingber. 2013. “An Artificial Vasculature for Adaptive Thermal Control of Windows.” *Solar Energy Materials and Solar Cells* 117: 429–36.

Imbabi, Mohammed Salah Eldin. 2012. “A Passive–Active Dynamic Insulation System for All Climates.” *International Journal of Sustainable Built Environment* 1 (2): 247–58.

Kosir, Mitja. 2016. “Adaptive Building Envelope: An Integral Approach to Indoor Environment Control in Buildings.” In *Automation and Control Trends*, edited by P Ponce, A Molina, and L Ibarra, 121–48. IntechOpen.

Looman, Remco. 2017. *Climate-Responsive Design A Framework for an Energy Concept Design-Decision Support Tool for Architects Using Principles of Climate-Responsive Design*. Vol. 01. Architecture and the Built Environment.

Loonen, Roel C.G.M., Marija Trčka, Daniel Cóstola, and Jan L.M. Hensen. 2013. "Climate Adaptive Building Shells: State-of-the-Art and Future Challenges." *Renewable and Sustainable Energy Reviews* 25: 483–93.

Perino, Marco, and Valentina Serra. 2015. "Switching from Static to Adaptable and Dynamic Building Envelopes: A Paradigm Shift for the Energy Efficiency in Buildings." *Journal of Facade Design and Engineering* 3 (2): 143–63.

Rotzetter, Aline C.C., Cristoph M. Schumacher, Stephanie B. Bubenhofer, Robert N. Grass, Lukas C. Gerber, M. Zeltner, and Wendelin J. Stark. 2012. "Thermoresponsive Polymer Induced Sweating Surfaces as an Efficient Way to Passively Cool Buildings." *Advanced Materials* 24 (39): 5352–56.

Taveres-cachat, Ellika, Steinar Grynning, Judith Thomsen, and Stephen Selkowitz. 2019. "Responsive Building Envelope Concepts in Zero Emission Neighborhoods and Smart Cities - A Roadmap to Implementation." *Building and Environment* 149: 446–57.

Zhang, Mingjie, Menghao Qin, Carsten Rode, and Zhi Chen. 2017. "Moisture Buffering Phenomenon and Its Impact on Building Energy Consumption." *Applied Thermal Engineering* 124: 337–45.