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Biophilic, photobiological and energy-efficient design framework of adaptive building façades for Northern Canada

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ABSTRACT

This paper develops an integrated design framework of adaptive building façades (ABFs) to respond to photobiological and thermal needs of occupants, biophilic factors, energy requirements and climatic features in Northern Canada, i.e. near and above 50°N. The paper discusses the importance of biophilic and photobiological factors and ABFs to improve occupants' health and human-nature relations and deal with the extreme climate in Northern Canada where non-adapted buildings that could negatively affect occupants' wellbeing. The paper shows that existing ABFs must be further developed for northern applications in terms of (i) the physical structure and configuration of components (ii) the design of solar shading/louver panels to address photobiological and biophilic requirements (iii) the development of lighting adaptation scenarios to respond to biophilic and photobiological needs, local photoperiods and energy issues, and (iv) the overall biophilic quality for accessibility to natural patterns. The ABFs' framework was developed in three phases including (1) process environmental data (2) produce adaptation scenarios, and (3) operate adaptation scenarios. The research discussed major issues of all phases that must be further studied, especially the development of hourly/daily/seasonally lighting adaptation scenarios. The paper develops a holistic parametric methodology to integrate and optimize major design variables of ABF's components.

Key words:

Climate-responsive building, Image-forming effects, Non-image forming effects; Thermal comfort; Adaptation scenarios; Extreme climate

Introduction

This paper draws attention to three major issues related to buildings and occupants' wellbeing in Northern Canada that include: (i) the photobiological and biophilic performance of existing Northern buildings (ii) the potential of adaptive building façades (ABFs) to deal with photobiological, thermal, biophilic and energy efficiency issues in such climates, and (iii) a design framework of ABFs to address occupants' needs and energy efficiency. The paper first underlines the importance of these issues in the context of Northern Canada. Then, four groups of key factors are identified to study the performance of buildings and façades in terms of photobiological, thermal, climatic, biophilic and energy efficiency requirements. Considering the identified factors, the performance of existing buildings and façade systems in Northern Canada was studied. The paper also discusses the potential and deficiencies of existing ABFs to address the identified factors in Northern Canada. The study finally develops a fundamental design framework of ABFs to deal with critical climatic conditions and occupants' needs in Northern Canada. The framework provides a ground to design and optimize ABFs in terms of biophilic, photobiological and energy efficiency factors. The proposed framework could be further developed to design adaptive healthy buildings in other climates and regions.

Importance of the study

Importance of photobiological and biophilic factors

Biophilic, photobiological and thermal performances of the space are main factors in designing healthy and climate-responsive buildings. Biophilic design intends to reconstitute human-nature relationships and enrich occupants' interactions with nature through developing life and lifelike processes and patterns in buildings [1-3]. The biophilic design approach is claimed to minimize adverse effects of human development, maximize the positive benefit of nature, and improve human well-being physiologically, psychologically, emotionally and cognitively [4-7]. Biophilic design guidelines offer several recommendations [8, 9] which could be adjusted to promote human-nature relationships in the extreme cold climate of Northern Canada [10, 11]. People spent ample time in buildings in such climates, thus the biophilic approach has greater benefits [12, 13]. Biophilic design has direct relationships with photobiological and thermal performance of buildings by recommending the human- and nature-friendly design of building components and indoor environments.

Lighting and thermal design approaches have recently focused on the nature-friendly and human centric strategies to properly respond to photobiological and physiological needs of occupants. In recent decades, thermal performance has received considerable attention. ASHRAE [14] is one of the reliable references published useful guidelines for the indoor thermal comfort zone and natural/mechanical ventilation in different buildings located in different climate zones. Photobiological requirements correspond to human centric lighting design demanding particular attention [15]. As stated by photobiological studies, light triggers many reactions in the human body, through the visual system [16, 17]. Human visual system responses to incident light have two components, namely image-forming (IF) and non-image forming (NIF) [18-20]. The IF responses result in image formation and the sense of vision [18, 19] whereas the NIF responses refer mainly to the light effects on circadian clocks (also known as body clocks) [21-23], alertness and performance [24, 25]. Human circadian clocks need to be entrained nearly, but not exactly, every 24 hours [21-23]. It is the local photoperiod that represents the main environmental time cues or 'zeitgebers (i.e. time giver or synchronizer)' to reset or synchronize circadian clocks [26-28]. IF and NIF systems demonstrate different responses to various light parameters such as quantity, spectrum, time and duration of impulses (for further details refer to Parsaee et al. [10], Refinetti [16], DiLaura et al. [18], CIE [20], Khademagha et al. [29], Berman and Clear [30], Khademagha et al. [31]). Occupants' IF and NIF responses/requirements are different regarding hourly/seasonally photoperiods and different activities in the building [32-34]. A proper intensity and chromaticity of light at the right time must be provided to occupants [20, 35]. NIF responses of occupants have recently been addressed in the context of built environments [20, 29, 36], whereas the IF responses have been widely studied [10, 20, 35]. Lighting guidelines and standards of North America have been developed for IF needs and negligible attention is given to NIF needs [18, 19, 37]. Neglecting NIF effects causes serious light-related diseases and disorders such as desynchronized circadian clocks, sleep problems, seasonal affective disorder (SAD), non-seasonal depression, [20] which have extensively been reported in high-latitude regions [28, 38-40].

Climatic challenges in Northern Canada

Buildings must provide Canadian Nordic population with a healthy and nature-friendly indoor environment, especially in terms of photobiological and biophilic aspects. However, responding to Northern occupants' biophilic and photobiological needs is challenging because of climatic conditions and the building design. Northern Canada refers to regions in near and above 50°N latitudes categorized into ASHRAE climate zones 7 and 8 [41] (see Figure 1-a). Climatic features drastically change by moving towards high latitudes and sub-Arctic regions of Canada [41-43] resulting in challenging living and working conditions [44, 45]. Seasonal photoperiods and solar radiation, the most influential factors on the climate and human lives [18, 26, 46], could change from a few hours of daylight in the winter to almost no-darkness during the summer in a high-latitude Canadian City such as Cambridge Bay, Nunavut, Canada [69.1°N] (Figure 1-b). As depicted in Figure 1-d, the solar altitude reaches the zenith of about 20° in the winter and 50° in the summer in Kuujjuaq. This situation affects climatic thermal features resulting in a negative surface energy budget, very low average air and surface temperatures and dominantly snowfall precipitations throughout the year [42, 46]. In such an extreme climate, Northern population has forced to spend a considerable time, more than 90%, inside buildings [12, 13]. Inuit people and Nordic inhabitants have adapted to the extreme climate whereas non-adapted occupants, such as workers and occupants from southern latitudes, are negatively affected [47, 48]. Efforts have thus far been directed towards thermal comfort and energy efficiency issues in designing buildings and façades without considering photobiological and biophilic requirements. The National Energy Code of Canada for Buildings (NECB) focuses on thermal issues and recommends a low window-to-wall ratio (WWR) or the fenestration-and-door-to-wall ratio (FDWR) for Northern regions, i.e. between 30% to 20% [49, 50] (see Figure 2). However, biophilic and photobiological studies strongly recommend to not unnecessarily decrease or restrict availability and accessibility to daylight and outdoor nature inside buildings because it can compromise people's health and wellbeing [8, 9, 35, 51]. Further research and developments are needed to consider and integrate biophilic and photobiological aspects in the design of buildings and façade systems in Northern Canada.

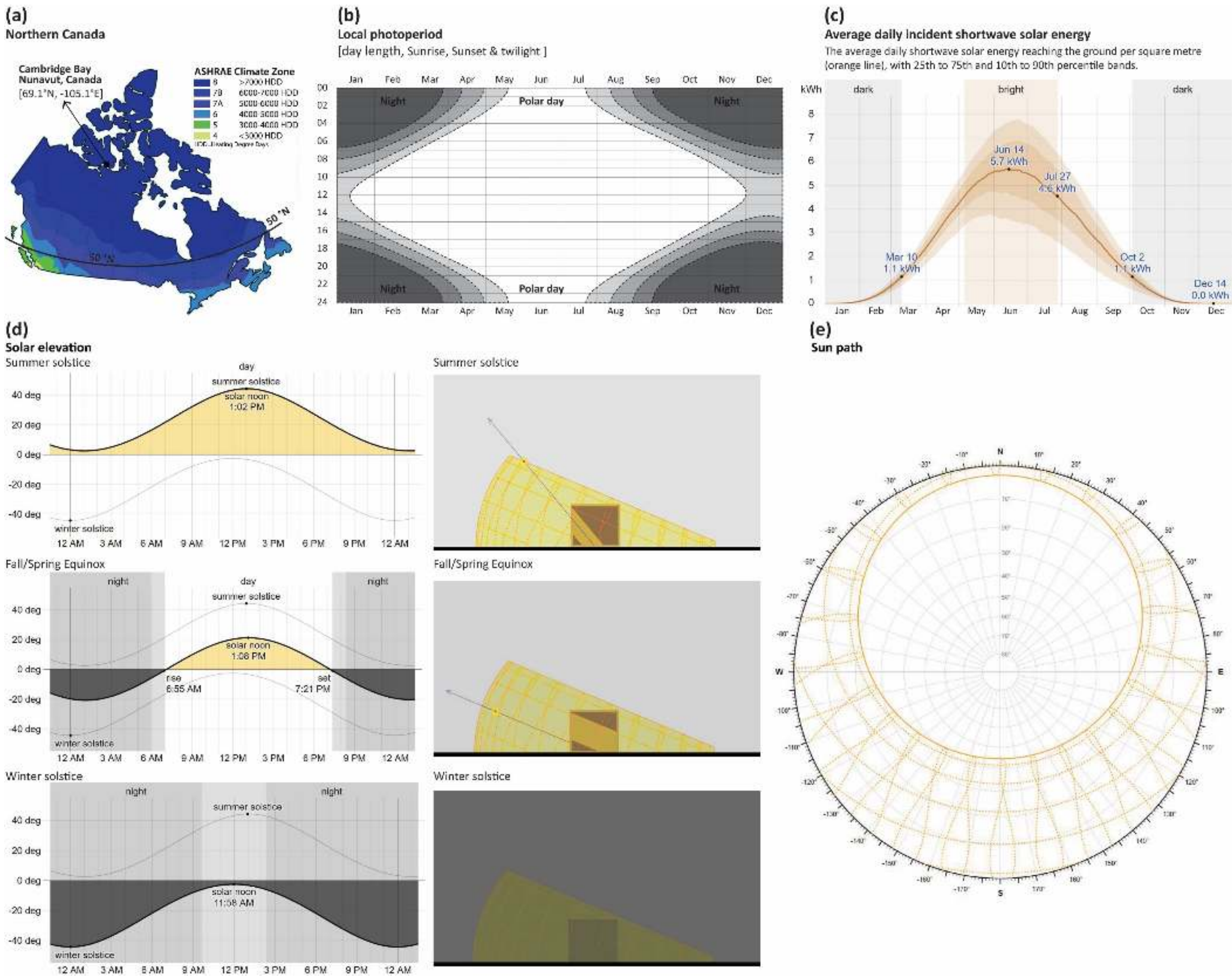
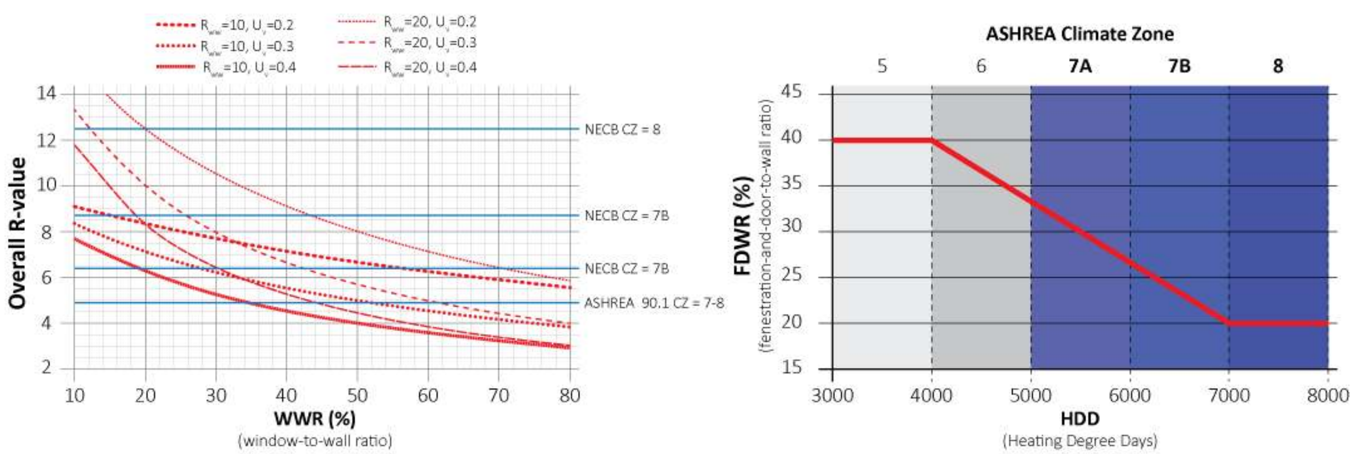


Figure 1. (a) Northern Canada located near and above 50° N categorized into ASHRAE climate zones 7 and 8 [41]. Lighting features of the climate in Cambridge Bay, Nunavut, Canada [69.1°N], including the (b) seasonal photoperiod and day/night length sun path (c) average daily solar energy (d) solar elevation in the summer and winter solstices and spring/fall equinox and (e) sun path geometry (figures are derived from weather spark [52] and online tools offered by Marsh [53])



Combined impact of thermal performance of mass walls and windows and WWR (CZ=climate zone, R_{ww} is whole-wall R-value, and U_v is window U-value)

Figure 2. National Energy Code of Canada for Buildings' (NECB) recommendations for the WWR, FDWR and R-value for Canada climate zones 7 and 8 corresponding to northern regions (retrieved from NRC [49,] Straube [50])

Importance of building façades and adaption strategies

Building components and façade systems affect biophilic, photobiological and thermal performances of the space. For example, windows as well as materials, textures and finishing colours of shading panels and surfaces have significant impacts on occupants' photobiological and thermal comforts [54-56]. The colour temperature of received light at individuals' eyes, one of the influential parameters in NIF responses [29, 57, 58], can be significantly manipulated by openings, spaces' elements and surfaces' materials, textures and finishing [18, 55, 58, 59]. The façade system, particularly, plays a key role in the development and design of such healthy climate-responsive buildings in Northern Canada [60, 61]. Façades are responsible for daylighting availability and connectivity to nature. They are in-between systems connecting occupants and the indoor environment to the outdoor climate [62-64]. Façade systems affect indoor environmental quality and control accessibility to the surrounding environment, natural cycles and daylighting [62, 65, 66]. The façade of Northern buildings must, therefore, be designed with respect to biophilic and photobiological guidelines as well as thermal comfort and energy efficiency issues [11, 67].

As a hypothetical solution, this paper draws attention to the potential of ABFs that could be developed particularly for biophilic and photobiological issues in Northern Canada. The core idea of building adaptation strategies is to facilitate the positive interaction of different contexts and actors in a design problem to offer satisfactory and reliable solutions [68-70]. Adaptation strategies and the climate-responsive design of buildings had traditionally been employed before the modern era and invent of mechanical systems for conditioning indoor environment [43, 71]. In this regard, adaptation strategies have, evidently, been appeared in vernacular architecture of different countries and climates like China [72], Vietnam[73], Japan [74], Iran [70, 75], Africa [76]. Adaptation strategies have also been employed in the vernacular settlements of Nordic people in extreme climatic conditions [77-83]. Such strategies in vernacular architecture are mainly based on increasing the environmental contact and maximizing advantages of nature. Adaptive façade systems have recently received increasing attention as a promising strategy to adapt buildings to human needs and natural conditions in different climates. In the past few years, several concepts of ABFs have been developed such as climate adaptive building shells [84], responsive building envelopes [66], intelligent façades [85], advanced integrated façades[86], smart façades [87], double skin façades [88], kinetic façades [89], biomimetic building skins [90], climate responsive shells and forms [91, 92] and adaptive façades with movable insulation panels [93, 94]. As presented in Figure 3, several buildings have also been designed and built with adaptation strategies for different uses and climates,

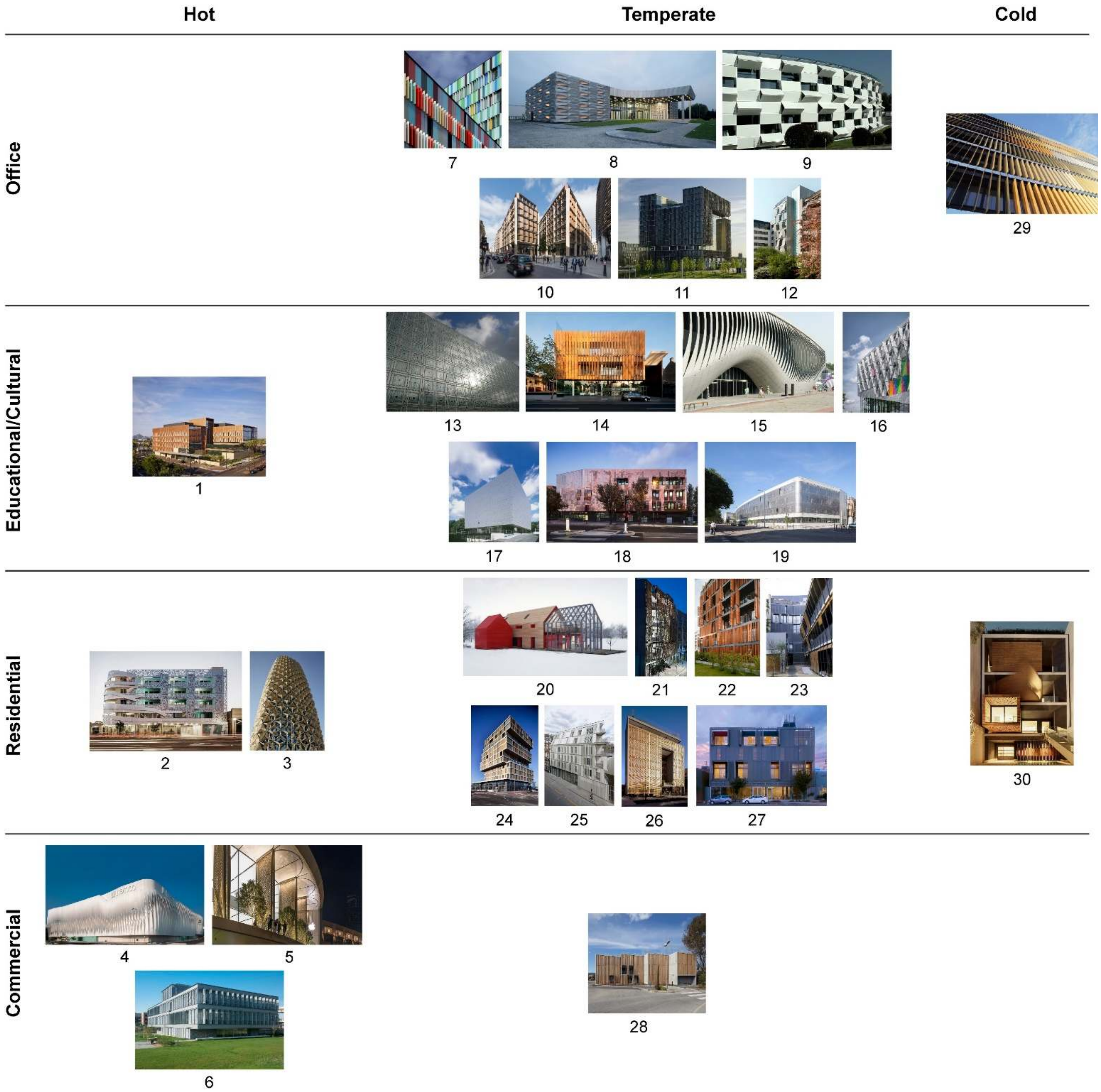


Figure 3. Some examples of adaptive façade strategies built for different building uses in various climates (see Appendix A for further information about these buildings and the courtesy of photos)

ABFs offer a potential solution to meet photobiological and biophilic needs of occupants, improve building energy efficiency and deal with the extreme climate in Northern Canada. ABFs point to the (self-) adjustment of façade systems to interior/exterior environmental conditions and needs of occupants in different climates [63, 95, 96] including Northern Canada. ABFs are defined as façade systems with intelligent, repeatable and reversible modification abilities for some of its functions, features or behaviours over the time [84, 97, 98]. These abilities adapt and modify the overall building performance according to dynamic environmental conditions and occupants' needs [84, 97, 98]. ABFs is claimed to offer mechanisms to respond appropriately to occupants' needs and environmental boundary conditions in different climates [97-99]. From this point of view, ABFs have the potential to provide Northern Canadian occupants with a healthy and comfortable indoor environment [10, 11, 100]. This paper contributes to the development of healthy, climate-responsive and energy-efficient ABFs for the application in Northern Canada.

Major performance indicators

To assess and develop façade systems for Northern Canada, the key factors addressing photobiological, thermal, climatic, biophilic and energy efficiency requirements should be established first. Four categories of fundamental factors could be defined in terms of the indoor environment and occupants' biological needs, outdoor climate, biophilic requirements and energy issues.

Biological needs' factors

Façade systems must be designed to address hourly/seasonally occupants' biological needs through adjusting indoor lighting and thermal environments. Biological needs refer to photobiological and thermal parameters. Thus, façades must be designed to respond to photobiological needs of occupants through meeting hourly/seasonally IF and NIF requirements for different activities inside buildings. Façades should also provide occupants with an appropriate thermal comfort zone for a specific climate class, as published by ASHRAE [14]. The following items are considered to assess façade systems in terms of photobiological and thermal comfort requirements:

- **Image-forming (IF) effects:** refer to the consideration of IF effects of lighting on occupants
- **Non-image forming (NIF) effects:** refer to the consideration of NIF effects of lighting and natural cycles on occupants
- **Thermal aspects:** refers to the consideration of heat exchange and airflow impacts of the system on occupants' thermal comfort

Climatic factors

Façade systems must appropriately respond and adapt to the outdoor climate and maximize the positive relationship with exterior environments. In the context of built environments, the major climatic factors include lighting and thermal features [14, 41, 101]. Lighting features mainly refer to daylight, seasonal photoperiods (e.g. light/dark cycles) and sun elevation [43, 101]. Thermal features mainly refer to surface and weather temperatures, humidity, wind, solar radiation and precipitation [102, 103]. In the extreme climate of Northern Canada, façade systems must be designed to outweigh the advantage of solar radiation and minimize the adverse effect of extreme cold weather through connecting indoors to outdoors when solar radiation is available and is needed [96, 104]. The following items are considered to assess building façades:

- **Lighting responsive:** refers to the façade's response to lighting aspects of the local climate

- **Thermal responsive:** refers to the façade's response to thermal aspects of the local climate

Biophilic factors

Façade systems must be designed with respect to biophilic recommendations, especially for high latitudes such as Northern Canada. Biophilic design propounds the human- and nature-friendly design of six specific features of the built environment including (1) visual and non-visual features (2) airflow and thermal features (3) acoustic features (4) colours and materials (5) shape and form and (6) design implications and space syntax (for further details, refer to Kellert and Calabrese [8], Browning et al. [9], Kellert [105]). Figure 4 displays characteristics of human, nature, buildings and façades with respect to northern-latitude climates and biophilic design recommendations proposed by Browning et al. [9] and Kellert and Calabrese [8]. No index or metric has thus far been developed to quantify and monitor the biophilic quality of a space [10, 106]. Some biophilic recommendations can still be considered, which are applicable to the design of façades for Northern climates, as the following items. As the paper is focused on façade systems in an extreme cold climate, biophilic recommendations for the design of indoor environments, such as greenery, has not been considered.

- **In-between space:** refers to the thickness of the space among façade skins which can be identified as a cavity (gap for airflow, heat transfer, etc.), corridor (sufficient thickness for crossing a person) or inhabitable (sufficient thickness for a sitting or living space, like a balcony)
- **View:** refers to the consideration of view to the surrounding environments and the connectivity to nature.
- **Colour:** refers to the consideration of nature-friendly colour.
- **Materials:** refer to the consideration of natural or nature-friendly materials.
- **Form:** refer to the consideration of biomimicry forms or nature-friendly shapes.

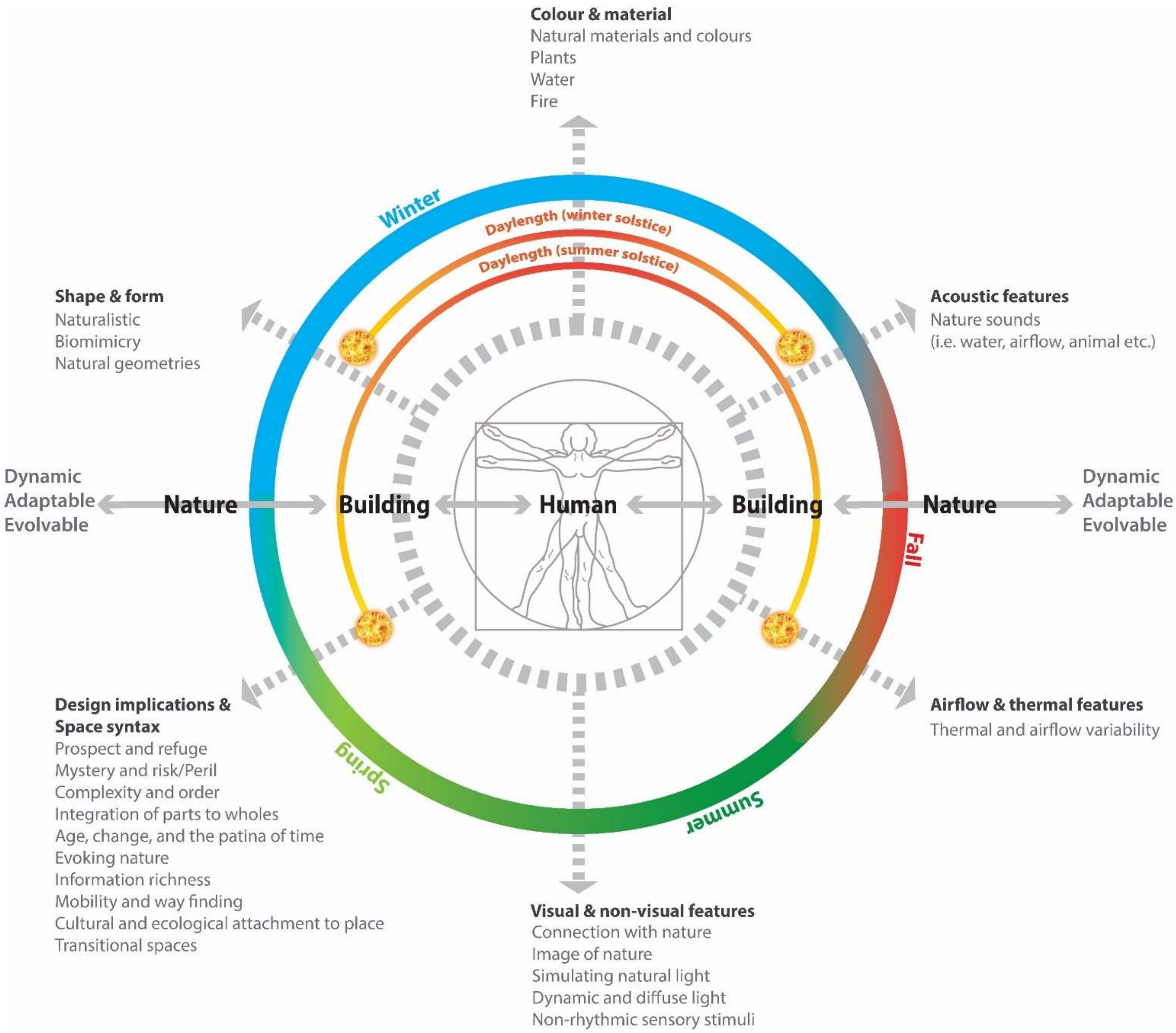


Figure 4. Characteristics of the human, nature and buildings with respect to biophilic design recommendations (based on Browning et al. [9] and Kellert and Calabrese [8]) and the extreme cold climate of northern latitudes

Energy factors

Biophilic design, occupants' needs and climate-responsive factors as well as the physical structure of façades could influence the overall energy performance of buildings. The major factors determining the total energy consumption of buildings include (1) climate (2) building façade (3) building energy and services systems (4) indoor design criteria (5) building operation and maintenance, and (6) occupants' behaviours [107-109]. Occupants' behaviour has reciprocal interactions with other factors in determining the energy consumption of buildings [110]. This study considers impacts of façade systems on the overall energy performance of the building, as the following item:

- **Energy efficiency:** refers to the positive effects on the overall energy performance of the building

Performance of façades in Northern Canada

Considering the assessments factors, façades of existing buildings in Northern Canada are designed with little considerations for the climate, photobiological needs and biophilic quality. As can be seen in Figure 5, typical buildings with a single-skin façade and small openings have most often been designed in Northern Canada. As shown in the following, such buildings consist of imported southern models that have been designed to only satisfy the thermal comfort demand.

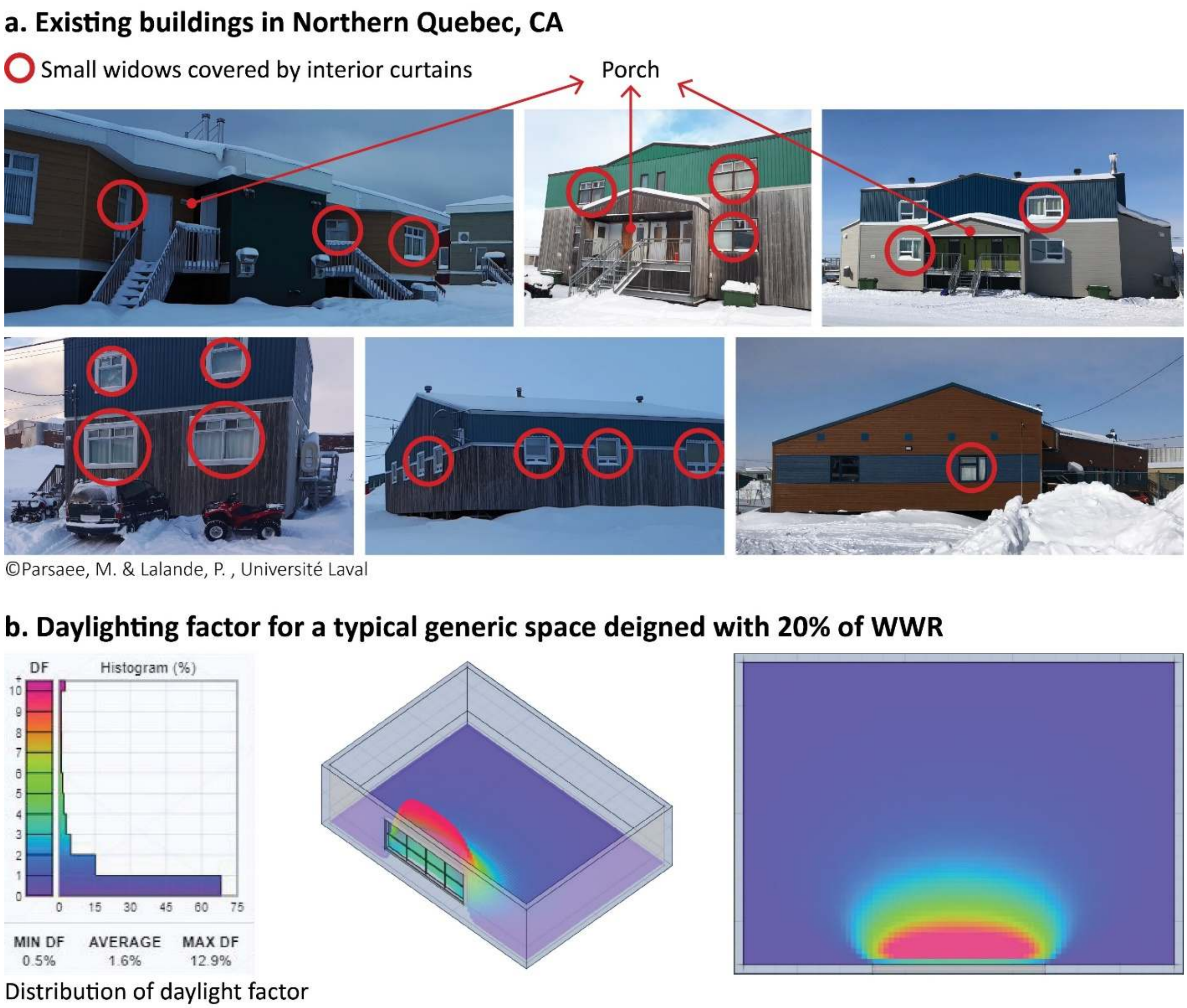


Figure 5. (a) Existing buildings in Northern Quebec (b) daylighting performance inside a generic space in existing buildings in Northern Quebec

In terms of biological needs' factors; *(i) Occupants' photobiological comforts:* the existing model of buildings and façades are designed with negligible consideration to solar radiation, daylight and local photoperiods. The building lighting relies mainly on artificial systems to fulfil basic IF needs while NIF needs have been neglected

[111]. As can be seen in Figure 5-a, small windows (low WWR/FDWR, i.e. around 20%) are most often designed based on the NECB's recommendation. Such small windows are covered by curtains most of the time on cloudy or clear sky conditions. This issue implicates the fact that the design strategy is not adapted and non-efficient because it does not meet occupants' light-related needs as well as yield the benefit of daylighting. Figure 5-b shows the low daylighting performance inside a generic space with a 20% WWR in Northern Quebec. As already been reported [112-115], such unhealthy indoor lighting environments could cause several light-related health issues in high-latitude regions like Northern Canada.

(ii) Occupants' thermal comforts: The thermal comfort zone is provided through using mechanical air conditioning systems. Existing strategy of low WWR/FDWR compromises the effective use of solar radiation for indoor thermal performance, especially when windows are covered by curtains.

In terms of climatic factors; No adaptation strategy is designed to connect indoors to outdoors in order to outweigh the benefit of the climate by responding to the availability of solar radiation adapted to occupants' needs. The low WWR/FDWR and high thermal resistance façade are designed to reduce indoor-outdoor interactions and isolate the indoor environment. Meanwhile, the single-skin façade is in direct contact to the harsh nature without any moderator or in-between space. As illustrated in Figure 5, a porch is designed in front of the entrance in some cases which could potentially act as a moderator, although it is not genuinely designed for such reasons and benefits.

In terms of biophilic factors; The existing buildings have very low biophilic quality because they severely disconnect occupants from exterior environments and natural cycles resulting in insufficient accessibility and view to nature and natural patterns. The form and colour of façades have a negligible biophilic quality. The use of wood is, however, increased the nature-friendly quality of façades. Moreover, the design of a porch in front of the building's entrance could be considered as an in-between space contributing to biophilic quality.

In terms of energy factors; small windows (low WWR/FDWR) and high thermal resistance façades are designed to minimize heat loss and increase overall thermal performance and energy efficiency of buildings in Northern Canada, as the ultimate goal of NECB. Such Energy conservation strategies impede interior-exterior exchanges and generate a mechanically controlled interior environment. There has therefore been a higher demand for artificial lighting and mechanical heating systems with negative environmental impact.

Performance of existing ABFs

The existing knowledge and practice of ABFs are critically reviewed in terms of the identified key factors as well as their applications in Northern Canada. The analysis of existing ABFs reveals key issues that must be further developed to meet requirements of all assessment factors, especially photobiological and biophilic, in Northern Canada. Table 1 presents the assessment of some constructed ABFs given in Figure 3. The overall assessment reveals the following points:

1. ABFs have most often been built with a cavity or a corridor as an in-between space among different layers and skins. Such ABFs were mainly deigned as double or multi-skin façade systems. Few cases were also designed with an inhabitable in-between space. Some ABFs have also been designed with solar shading/louver panels.
2. The configuration of the skins has been adjusted regarding climatic conditions.
3. A variety of adaptation mechanism, behaviour and processes have been developed using smart, automatic and high-tech systems to manual and low-tech strategies. The existing practices of such smart systems were mainly designed to follow the sun path and measure light and heat levels of indoors, as can be seen in the Swiss Federal Railways' building. Motorized systems have been used for several dynamic behaviours and automatic executions.
4. The examples of ABFs were most often designed to provide occupants with thermal and visual comfort through responding to solar radiation and daylighting. Their impact on energy efficiency has mainly been considered in terms of ventilation, air conditioning systems, artificial lighting and CO_2 emission. The analysis of energy performance is not available for all of the cases.
5. Non-image forming (NIF) requirements have received negligible attention in designing ABFs' system. In some cases, NIF considerations are limited to the use of artificial lighting systems.
6. Most of the ABFs were designed with respect to views to surrounding environments and connectivity to nature as well as to use bio-based forms and materials and nature-friendly colours. The impact of such materials and colours on NIF responses of occupants has not yet been considered.

To apply in Northern Canada, existing ABFs' must be further developed particularly in terms of the following issues. The next section proposes a fundamental design framework through which ABFs could be assessed and optimized for higher performance.

I. The physical structure and configuration of components
II. The design of solar shading/louver panels to address biological needs, in particular IF and NIF responses, biophilic requirements and energy issues
III. The development of lighting adaptation scenarios to respond to biophilic and biological needs (i.e. IF and NIF responses), local photoperiods and energy issues
IV. The overall biophilic quality for accessibility to natural patterns

Table 1. An analysis of some constructed adaptive building façades (the sources of information are given in Appendix A)

	Case	Building Class	Location															
1	University of Arizona Cancer Centre	Medical/ Educational	Phoenix, AZ, USA	S	P	P	H	✓	✓	✓	✕	✓	Ca	✓	✓	✓	✓	✓
2	The La brea Affordable Housing	Residential/ Commercial	West Hollywood, CA, USA	S	P	P	H	✓	✓	✓	✕	N/A	Co	✓	✕	✕	✓	N/A
3	Al Bahar Towers	Residential tower	Abu Dhabi, UAE	D	S	A	H	✓	✓	✓	✕	✓	Ca	✓	✓	✕	✓	✓
4	Liverpool Department Store	Commercial	Villahermosa, Mexico	S	P	P	H	✕	✕	N/A	✕	N/A	Ca	N/A	✓	✓	✓	N/A
5	Apple Dubai Mall	Commercial	Abu Dhabi, UAE	D	H	H	H	✓	✓	✓	✕	N/A	In	✓	✕	✕	✕	✓
6	M2 Technological Building	Educational	Villamayor, Spain	D	S	A	H	✓	✓	✓	✕	✓	Co	✓	✕	✓	✕	N/A
7	Mac567	Office	Milan, Italy	H	S	AP	T	✓	✓	✓	✕	N/A	Ca	✓	✓	✓	✕	✓
8	S2OSB Headquarters & Conference Hall	Office/ Conference hall	Hendek, Turkey	S	P	P	T	✓	✕	✓	✕	N/A	Ca	✓	✕	✓	✓	N/A
9	Kiefer Technic Showroom	Office	Bad Gleichenberg, Austria	D	H	H	T	✓	✓	✓	✕	✓	Ca	✓	✕	✕	✓	✓
10	Bloomberg European Headquarters	Office	London, UK	D	P	A	T	✓	✓	✓	✕	✓	Ca	✓	✓	✓	✓	✓
11	Q1	Office	Essen, Germany	D	S	A	T	✓	✓	✓	✕	✓	Ca	✕	✕	✓	✓	✓
12	Friedrichstrasse 40	Office	Berlin, Germany	H	U	AP	T	✓	✕	✓	✕	✓	Ca	✓	✓	✕	✕	N/A
13	Arab World Institute	Cultural	Paris, France	D	S	A	T	✓	✕	✓	✕	✓	Ca	✓	✕	✕	✓	✓
14	Surry Hills Library & Community Centre	Library/ community centre	Surry Hills, NSW, Australia	D	S	A	T	✓	✓	✓	✕	✓	Ca	✓	✓	✓	✕	✓
15	One Ocean	Pavilion	Yeosu, South Korea	D	S	H	T	✓	✕	✓	✕	N/A	Ca	✓	✕	✕	✓	N/A
16	SDU Campus Kolding	Educational	Kolding, Denmark	D	S	H	T	✓	✓	✓	✕	✓	Ca	✓	✓	✓	✕	✓
17	The Mutable House	Educational	Cologne, Germany	D	U	A	T	✓	✓	✓	✕	N/A	Ca	✓	✕	✕	✓	N/A
18	Claude Debussy (Music) Conservatory	Cultural	Paris, France	D	U	M	T	✓	✓	✓	✕	N/A	Ca	✓	✕	✕	✕	N/A
19	Institut Des Sciences Analytiques	Educational	Villeurbanne, Lyon, France	S	P	P	T	✓	✓	✓	✕	✓	Co	✕	✕	✓	✕	N/A

20	Sliding House	Residential	Suffolk, UK	D	U	A	T	✓	✓	✓	✗	N/A	Ca	✓	✓	✓	✗	N/A
21	Ipera 25	Residential	Istanbul, Turkey	D	U	M	T	✓	✓	✓	✗	✓	Ca	✓	✓	✓	✗	N/A
22	Wilanowska Housing Complex	Residential	Warsaw, Poland	D	U	M	T	✓	✓	N/A	✗	N/A	In	✓	✓	✓	✗	N/A
23	Rue Des Suisses	Residential	Paris, France	D	U	M	T	✓	✓	✓	✗	N/A	In	✓	✓	✓	✗	N/A
24	Majske Poljane	Residential	Nova Gorica, Slovenia	D	U	M	T	✓	✓	✓	✗	✓	Ca	✓	✓	✓	✗	✓
25	10 Housing Units Castagnary	Residential	Paris, France	D	U	M	T	✓	✓	✓	✗	✓	Ca	✓	✗	✓	✗	N/A
26	Noi Hotel	Residential/ Recreational	Vitacura, Chile	S	P	P	T	✓	✓	✓	✗	✓	Co	✗	✓	✓	✗	✓
27	Cherokee Lofts	Residential	Los Angeles, CA, USA	D	U	M	T	✓	✓	✓	✗	✓	In	✓	✗	✓	✗	✓
28	Social Housing & Shops	Residential/ Commercial	Mouans-Sartoux France	D	U	M	T	✓	✓	✓	✗	N/A	In	✓	✓	✓	✗	N/A
29	Headquarters of the Swiss Federal Railways	Office	Bern, Switzerland	D	S	H	C	✓	✓	✓	✗	✓	Ca	✓	✓	✓	✗	✓
30	Sharifi-Ha House	Residential	Tehran, Iran	D	U	M	C	✓	✓	N/A	✗	✓	In	✓	✓	✓	✗	N/A

Adaptation mechanism	Biological needs' factors	Climate factors	Biophilic factors	Energy factors
Adaptation behaviour [**D**ynamic, **S**tatic, **H**ybrid]	Image forming (IF) effects	Lighting responsive	In-between space [**Ca**vity, **Co**rridor, **In**habitable]	Energy efficiency
Adaptation process [**S**mart, **P**re-set, **U**ser-defined, **H**ybrid]	Non-image forming (NIF) effects	Thermal responsive	View	
Adaptation operation [**A**utomatic, **M**anual, **H**ybrid, **P**re-set]	Thermal aspects		Colour	
			Material	
			Shape and form	

Climate class

N/A The information is not available

ABFs' design framework

To further develop for Northern Canada, a fundamental framework of ABFs is defined in three basic phases including (1) process environmental data (2) produce adaptation scenarios, and (3) operate adaptation scenarios, as depicted in Figure 6. As can be seen, ABFs should first monitor and process environmental data to produce adaptation scenarios which are defined as entire protocols and profiles to adjust the façade system to boundary conditions, i.e. photobiological, thermal, climatic, biophilic and energy factors. ABFs must then operate the produced scenarios through some behaviours in physical components. The adaptation behaviour is defined as the dynamic, static or hybrid behaviour of ABFs' system in response to boundary conditions. As shown in the fundamental concept of ABFs, the phases will be run several times in the case of dynamic behaviour and automatic execution whereas they will be run once during the design process in the case of static behaviour and manual/pre-set execution. The following sections explain the phases in detail.

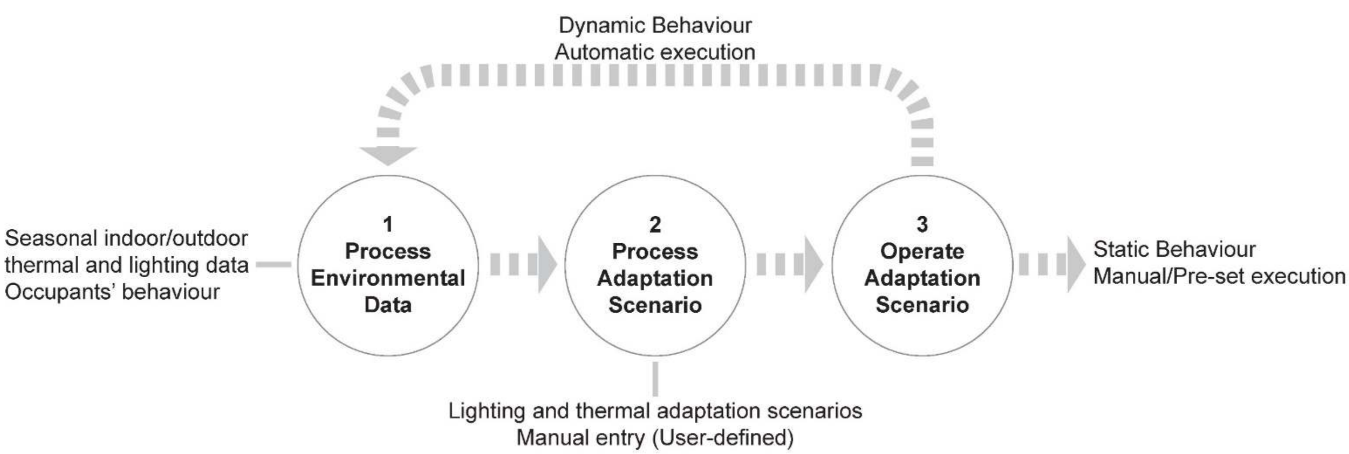


Figure 6. The fundamental concept of an ABF

Phase 1: Process environmental data

Seasonal indoor/outdoor thermal and lighting data as well as occupants' behaviour should be monitored and analysed to produce lighting and thermal adaptation scenarios. Several metrics and parameters have extensively been developed to capture and analyse thermal and lighting data. Appendix B, part-1 and part-2, provide a list of references giving further details about different photobiological and thermal metrics, parameters and analysis methods. Methods and metrics should ultimately offer an integrated spatiotemporal analysis of IF and NIF effects, thermal performance and energy saving aspects in the building. To monitor occupants' behaviour and environmental parameters, a sensory environment and a network of actuators could be developed to detect (i) the presence of individuals in the space (ii) their interactions towards building components and façade systems, and (iii) lighting and thermal parameters of the environment. Occupant-building interactions have been simplified to limit actions such as controlling shades, blinds, doors, windows, lighting systems, HVAC systems, thermostat settings and electrical equipment (refer to references provided in Appendix B, part 3). To develop sensory environments, different low- and high-tech tools and devices have recently been developed. Such detection systems could be considered for a particular space during the early stage of design, renovation or post occupancy (See Figure 7). Detection systems are mostly considered as a part of control systems for buildings and façade components. Furthermore, different data mining and machine learning techniques have also been developed to organize, analyse and interpret behaviours and patterns. Appendix B, part 3, provides a list of references discussing details and challenges related to occupancy detection technologies and data mining methods. Environmental data and occupants' behaviour patterns could be represented in the virtual reality of the space [116]. Figure 7 illustrates a schematic example of an occupancy detection system combined with a virtual reality visualization model. The visualization of environmental data could further improve occupants' interactions towards building and façade systems. Such virtual reality environments and visualization of environmental data and occupants' behaviour could also enhance designers' perception regarding building performance and architectural choices during early stages of design or post occupancy evaluations. Appropriate tools and methods must be employed to be functional in the extreme cold climate of northern latitudes.

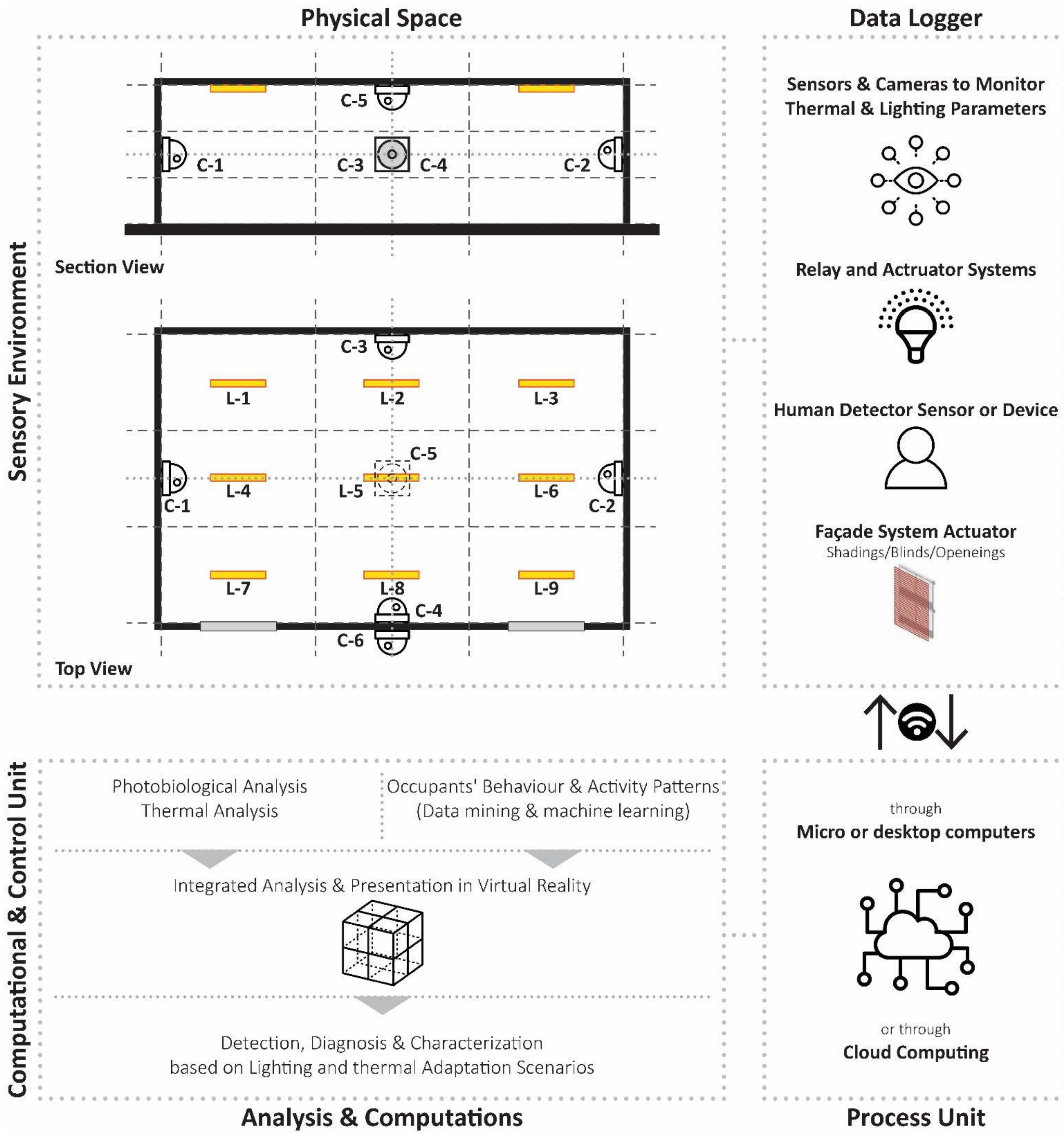


Figure 7. A schematic example of occupancy and environment detection/control system combined with a virtual reality visualization model (developed based on Parsaee et al. [116])

Phase 2: Process adaptation scenarios

The core of ABFs is to process appropriate lighting and thermal adaptation scenarios which must be produced to meet photobiological, thermal, biophilic and energy requirements in Northern Canada. Adaptation scenarios could be processed through different strategies such as smart (intelligently evaluated and adjusted to boundary conditions after/before every run), pre-set (defined, optimized and fixed during the design of ABFs and will remain constant throughout the façade lifecycle), user-defined (occupants define scenarios manually), or hybrid (the pre-set or smart modes combining with a user-defined mode). Table 1 presents different strategies used in some examples of ABFs. As can be seen in the studied examples, façade systems have been equipped with sensors and data loggers in the case of smart and hybrid scenario processes. The manual entry (user-defined) of adaptation scenarios must be available by which occupants have an opportunity to apply their preferences, although their adjustments might come in conflict with the optimum situation [99, 117].

ABFs require two basic adaptation scenarios, i.e. thermal and lighting. Thermal adaptation scenarios could be developed with respect to climatic conditions and recommendations offered by ASHRAE, WELL and biophilic studies. Considering the very low average temperature of high latitudes, thermal scenarios must be designed to maximize solar heat gains and minimize thermal losses when heating systems are running. The sun path and local photoperiod of northern latitudes could potentially increase heat gains during long days of the summer. Depending on the location, this issue could positively affect the thermal performance, i.e. heating loads, of the space. Meanwhile, heat losses must be controlled during long nights of the winter coming with an extremely low average temperature. For example, Figure 8 illustrates the outdoor thermal comfort in the climate context of Resolute Bay, Nunavut, Canada. As can be seen in Figure 8, the outdoor thermal features offer no comfortable condition throughout the year. The local solar patterns, however, offer a great potential to increase solar heat gains from March to September (see Figure 1-c and e). The sun path also makes solar heat gains available for almost all façade's orientation facing east, south, west or north. Therefore, the façade system must be designed to maximize solar heat gains in order to reduce mechanical/electrical heating system and energy consumption. Considering solar patterns, there is nearly zero solar heat available during January, February, October, November and December (see Figure 1-c and e). The façade system could be designed to operate a thermal scenario to reduce building heat losses by converging openings with insulated panels (for further information of such panels refer to Montier et al.[93] Montier et al. [94]). In this regard, thermal adaptation scenarios must be synchronized with lighting adaptation scenarios in order to offer sufficient connectivity and accessibility to natural light and local patterns for photobiological and biophilic requirements.

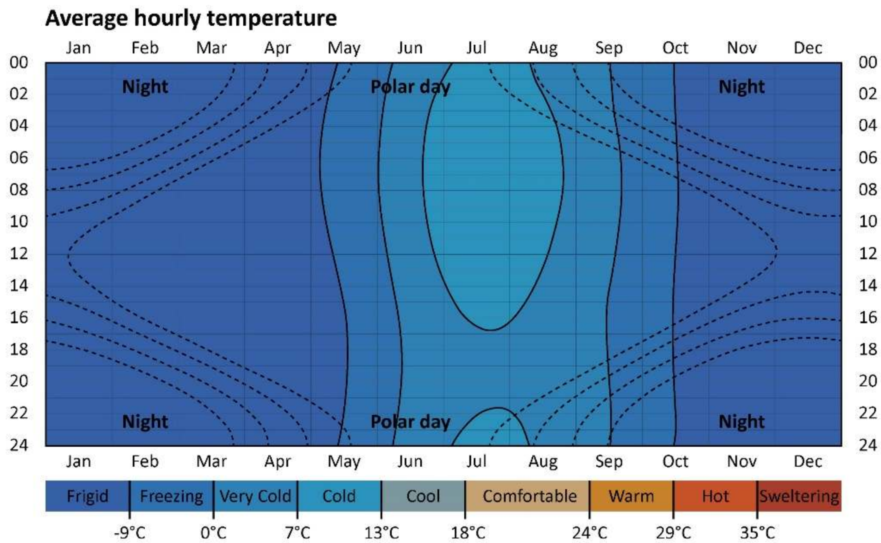


Figure 8. Thermal features of the climate in Cambridge Bay, Nunavut, Canada (retrieved from Weather spark [52,] Marsh [53])

Lighting adaptation scenarios must be developed with respect to hourly/daily/seasonally biophilic, photobiological, thermal and energy requirements in the context of local photoperiods for different building uses and indoor activities. Numerous research has thus far reported the IF and NIF effects of different light features such as intensity, colour temperature and time of exposure, but no adaptation scenario has yet been studied in order to establish a scientific base for hourly/daily/seasonally changes of indoor lighting features [118]. Due to the strong photoperiod and harsh climate, developing such lighting adaptation scenarios for Northern Canada is more challenging, especially in terms of photobiological and biophilic requirements. In general, a proper lighting must be provided at the proper time for different activities [35]. Sufficient darkness or dim light should also be provided when occupants need sleeping or resting in specific spaces such as bedrooms [119]. Meanwhile, sufficient connectivity to natural light and patterns must be accessible to occupants [118]. Table 2 summarizes the principle criteria that must be considered in the development of lighting scenarios. Table 2 briefly points that lighting adaptation scenarios should offer hourly/daily/seasonally patterns and thresholds (maximum / minimum / average) of intensity and colour temperature of indoor lighting with respect to IF and NIF effects, the biological and social day/night, building uses and activities.

Table 2. Premises and criteria for developing lighting adaptation scenarios (extracted from DiLaura et al. [18,] CIE [20, 35,] International WELL Building Institute [119,] Lucas et al. [120,] Rea and Figueiro [121,] Boivin and Boudreau [122,] Konis [123])

Premise	
1	The biological night starts from around 19:00 to7:00. Note that social day/night should be considered for adaptation to the particular activity, behaviour and culture.
2	A high Equivalent Melanopic Lux (EML) during the day is usually supportive for alertness, the circadian rhythm and a good night's sleep. A low EML in the evening and at night facilitates sleep initiation and consolidation.

3	The light dose thresholds for IF and NIF purposes include: a. Between 30 to 500 lux on horizontal work plan for visual comfort depending on the task and space function b. 100 lux or l00 EML on the vertical plan at eye level have 50% impacts on melatonin suppression. c. 200 lux or 200 EML on the vertical plan at eye level have 90% impacts on melatonin suppression d. A maximum of 50 to 250 lux or EML for a comfortable residential space depending on the task e. Between 250 to 350 for a commercial/office space with high vigilance and task performance
4	The daily timing of light impulse divides into four periods as following. These periods are based on the photobiological research. Note that the social night/day-time changes regarding people and society. I. 7:00 to 9:00 for the biological waking time and becoming vigilant II. 9:00 to 19:00 for the biological day and being highly vigilante for working III. 17:00 to 19:00 preparing for the biological night IV. 19:00 to 7:00 for the biological night and becoming less vigilant
5	Light dose should be minimum before sleep time.
6	During the sleep time, a complete darkness is required.
7	Blue-enriched light should be minimized before the sleep time. It can be maximized during 9:00 to17:00. In the morning (from 7:00 to 9:00), it can be used to increase alertness and synchronize the body clocks. Note that blue-enriched light has significant NIF impacts in the early morning which is recommended.

Connectivity and accessibility to natural light and local photoperiods must be prioritized as the primary source of indoor lighting and should not be compromised or replaced by artificial lighting systems. More specifically, lighting adaptation scenarios must maximize the use of natural light and nature-view in buildings, as the main source of lighting when it is available. Lighting scenarios should, then, be combined with artificial lighting, particularly tenable light-emitting diode (LED) systems, when natural light is not available. During the past few years, LED systems and smart lighting have been developed to respond to photobiological needs, especially NIF effects [124, 125]. Many studies have been conducted to investigate and improve the impact of LED and smart lighting systems on visual performance, circadian clocks, alertness, cognitive performance and sleep disorders [125-128]. LED systems are also reported being energy efficient [125]. Despite all these developments, biophilic and photobiological studies have emphasized that the design priority should be given to natural light and connection [8, 9, 35, 105].

Façade systems must be designed to enable, control and filter daylighting based on adaptation scenarios. During dark or very low-daylight hours, LED and smart lighting technologies can be used and adjusted to provide appropriate intensity and colour temperature required for hourly IF and NIF needs for a particular space or activity. The scenarios must be adjusted for different orientation of the space because of the annual solar geometry which provides different periods and amount of daylighting on north, east, south and west façades. Considering all these discussed challenges and issues, Figure 9 shows a potential hourly/seasonally adaptation scenario developed for an office space in Resolute Bay. As can be seen, the scenario offers the maximum use of daylighting when it is available during the work time over the day and the year. The scenario also proposes the adaptation to NIF needs of occupants through adjusting the colour and intensity of indoor lighting environment based on the premises in Table 5. LED systems could be used and programmed to provide the proposed indoor lighting and follow the adaptation scenario when daylighting is not available in the winter and cloudy days. The openings could be covered by movable insulation panels to reduce heat losses and improve the overall thermal performance when the building is not occupied. Noted that, although it would be almost dark outside, connectivity with outdoor nature must be provided during the winter days because of biophilic requirements highlighting several aspects and quality of nature (for further details read Kellert and Calabrese [8], Browning et al. [9], Kellert [105]). Similar lighting adaptation scenarios could be developed for needs of different building uses and activities such as health care, schools and residences.

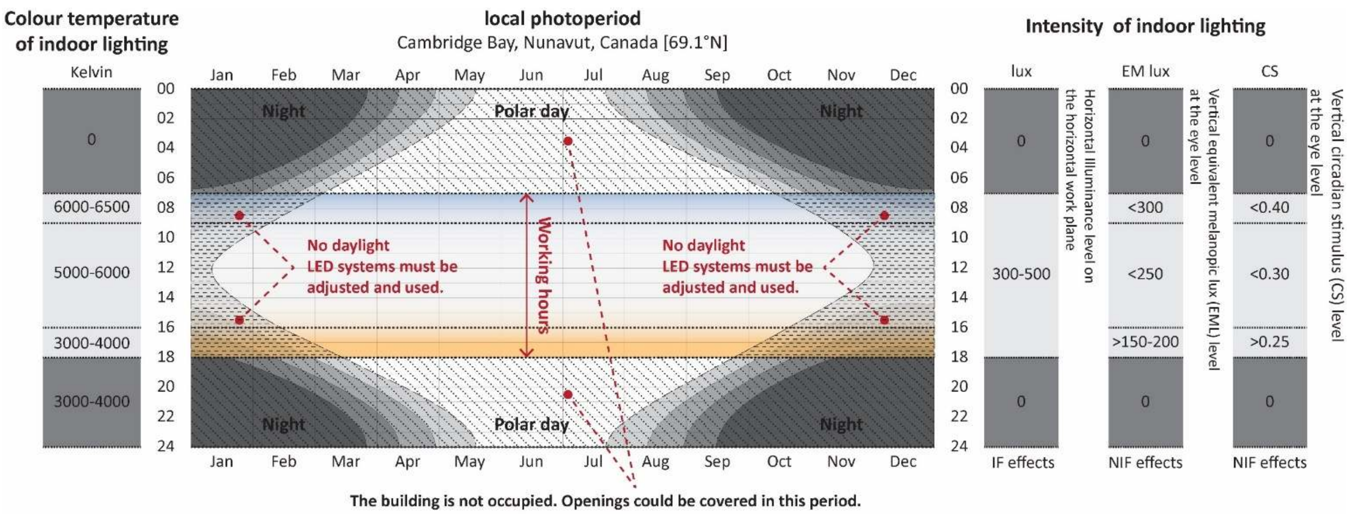


Figure 9. A potential hourly/seasonally lighting adaptation scenario for office buildings in Cambridge Bay, Nunavut, Canada.

Phase 3: Operate adaptation scenarios

The produced scenarios must be operated by ABFs in order to adjust the indoor environment to the expected criteria and thresholds. Operational strategies could be considered as automatic (i.e. motorized systems), manual (i.e. non-motorized system performing by human power), hybrid (including both options of automatic and manual) and pre-set (being configured and fixed in advance including smart materials). An appropriate adaptation behaviour must also be developed to operate the scenarios including dynamic, static and hybrid mechanisms. Dynamic behaviours are accomplished through performing movements and motions, such as folding, sliding, rolling, expanding and transforming, in some components or layers of the façade either automatically or manually. Static behaviours rely on material properties, such as phase change materials or smart widows. Hybrid behaviours are a combination of dynamic behaviour and material properties. Table 1 summarizes different adaptation behaviours and operations in existing examples. As can be seen, a higher technology, financial investment and technical considerations have been used for dynamic behaviours and automatic executions.

To operate adaptation scenarios, ABFs' physical structure must be developed and optimized to meet biophilic, photobiological, thermal and energy requirements in Northern Canada. One promising model is multi-skin façade (MSF) systems consisting of a solar shading/louver system, an in-between space (cavity, corridor or inhabitable), and exterior/interior skins with thermal resistance and solar transmittance features (see Figure 10). MSFs, such as double or triple skin systems, have potentials to run different adaptation behaviours and to operate different lighting/thermal scenarios in the extreme climate of Northern Canada. MSFs can reduce heating loads by trapping solar radiation in the cavity which results in the increase of the cavity air temperature. This is a positive advantage in the extreme cold climate of Northern Canada. Shading panels can also improve indoor daylighting performance inside buildings and control glare during the day. Through improving thermal and daylighting performance, MSFs could contribute to energy saving in Northern Canada. As a higher biophilic quality, the in-between space can be designed as a place for sitting (like a patio or porch) which is protected from strong winds, heavy rain and snow throughout the year. In case of designing a cavity, it must be sealed in the extreme cold weathers due to technical aspects and the risk of freezing and snow accumulations. In brief, multi-skin systems claimed having the following potentials and benefits.

i. **Higher thermal, daylighting and energy performances** (for details refer to [84, 129-137]):
ii. **Higher overall biophilic quality by designing an inhabitable in-between space or cavity** (for details refer to [133, 138, 139])
iii. **Higher long-term economic benefits** (for details refer to [99, 130])

The components' configuration of MSF systems must be adjusted and optimized for different applications in northern latitudes of Canada. Figure 10 proposes several possible configurations of a multi-skin system. Figure 10-cases 1, 2 and 3 suggest different configurations of thermal resistance and solar transmittance components without using solar shading/louver panels. As can be seen in Figure 10-case 1, both interior and exterior skins could be designed with thermal capacity. MSFs can have the exterior skin with thermal resistance while the interior skin acts as a separator wall with solar transmittance, as illustrated in Figure 10-case 2. The thermal resistance skin could also be designed as the interior component and the high solar transmittance skin acts as the exterior component (see Figure 10-case 3). Cases 4 to 7 illustrate different configurations of solar shading/louver panels. As can be seen, shading panels could be located in front of or behind the exterior skin (Figure 10-cases 4 and 5). It can also be located at the interior skin (Figure 10-cases 6 and 7). The suggested configurations of skins and components could significantly affect solar heat gain and accessibility to daylighting and outdoor climates. Figure 10-columns c and d present daylighting and solar heat gain behaviours of all cases based on rules of thumb. Table 3 also summarizes some recommendations for the application of multi-skin façades in cold climates and winters which could be considered in future developments for Northern Canada.

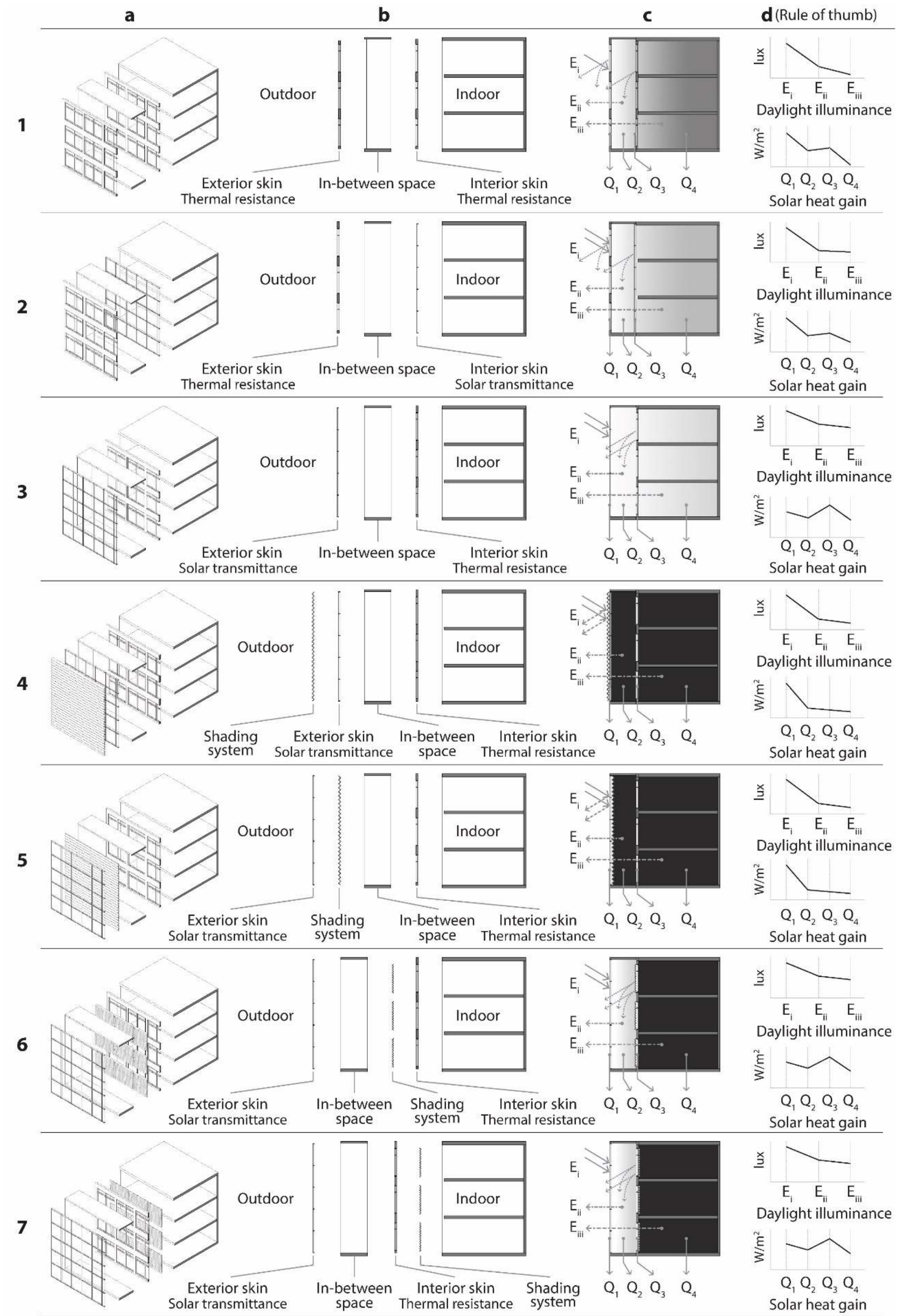


Figure 10. Different components' configurations of a multi-skin façade (MSF)

Table 3. Some recommendations for the application of multi-skin façades in cold climates and winters which could be considered in future developments for Northern Canada (given by Ghaffarianhoseini et al. [130,] Barbosa and Ip [132,] Poirazis [134,] Mingotti et al. [135,] Gratia and De Herde [136,] Jiru et al. [137])

Remark
• Double glazing with higher thermal insulation is likely to be applied at the inner layer of the façade in order to reduce the radiative and conductive components of heat transfer across the façade.
• Tinted glass or coating can be used to control the heat flux through a glazed façade.
• The low-e film should be applied on either surface facing the gap of double glazing.
• The inner skin could be designed with lower thermal resistance when a low-e-tinted inner glazing surface is used.
• The use of single glazing with high transmittance at the external layer allows for a high heat gain into the cavity, thus increases the buoyancy force for natural ventilation.
• External/in-between solar shadings are more effective than internal shading devices.
• Dark-coloured blinds inside the cavity increase the temperature more than light-coloured.
• The position of the blinds inside the cavity (outer, middle, and inner) have more effect on the distribution of temperature, velocity and solar heat gain compared to the angle of the slat.
• The temperature of the inner glass surface becomes higher when the shading devices are located close to it.
• The application of the thermal mass on the shading device results in energy saving.

The design variables of components must be identified and a platform must be developed to adjust and optimize the configuration of ABFs' physical structure in terms of biophilic, photobiological, thermal and energy requirements for a particular building in Northern Canada. Two groups of (a) primary and (b) secondary variables should be considered for designing and optimizing the physical system. Primary variables correspond to main architectural configurations including (1) the depth of in-between space, that could be a cavity, corridor or inhabitable, (2) the window-wall ratio (WWR) (3) the size of shading panels by considering the number, width and thickness, and (4) the tilted angle and orientation of panels. Secondary variables are related to the detail of the architectural design and characteristics of elements including details and characteristics of skins and shading panels in terms of the (i) material (ii) colour scheme (iii) reflectivity (iv) form, (v) motion related to dynamic or static behaviours. Such variables could potentially influence photobiological, thermal, biophilic and energy efficiency performance of buildings, as discussed in the previous sections.

Parametric studies could finally be conducted to assess and optimize variables by producing different cases and prototypes. Figure 11 shows a matrix chart of primary and secondary design variables in relation to performance indicators which can be used for future parametric studies of ABFs' physical components. As offered in Figure 11, the primary variables of the system can be first designed and assessed, then the secondary variables can be considered. For example, it can first design and assess ABFs which consisted of different WWRs, a cavity or corridor among their layers and various sizes of horizontal shading panels. The optimum output case of the assessment for primary variables could be the input for the design and assessment of the secondary variables. That means, for example, an ABF with 60% of WWR, a corridor-depth of in-between space, and horizontal medium size shading panels will be the input case for the assessment of different colour schemes, reflectivity and forms of skins and panels. The variables could be considered to be dependent or independent depending on the objective, available facilities and budget of the study.

The variables' combination could parametrically change for different analysis in order to find out a preferred high-performance case. A rating system, as depicted in Figure 11, could be used to assess the biophilic, photobiological, thermal and energy performances of every case. The performance indicators could have inverse relationships. For example, higher WWRs could potentially improve biophilic and NIF factors in terms of accessibility to natural light an outdoor nature. However, a high-WWR could associate with higher risk of glare and visual discomfort and heat losses. In this regard, several models and approaches have thus far been developed to optimize façades in terms of lighting, thermal and energy performance (see Appendix B, part-4 for some example studies). One architecturally interesting approach is to use the 'liberty index'[104] showing whatever the configuration has a net decrease in energy consumption while responding to minimal daylighting values. This could give architects and designers more freedom to explore, innovate and make high performance architectural choices.

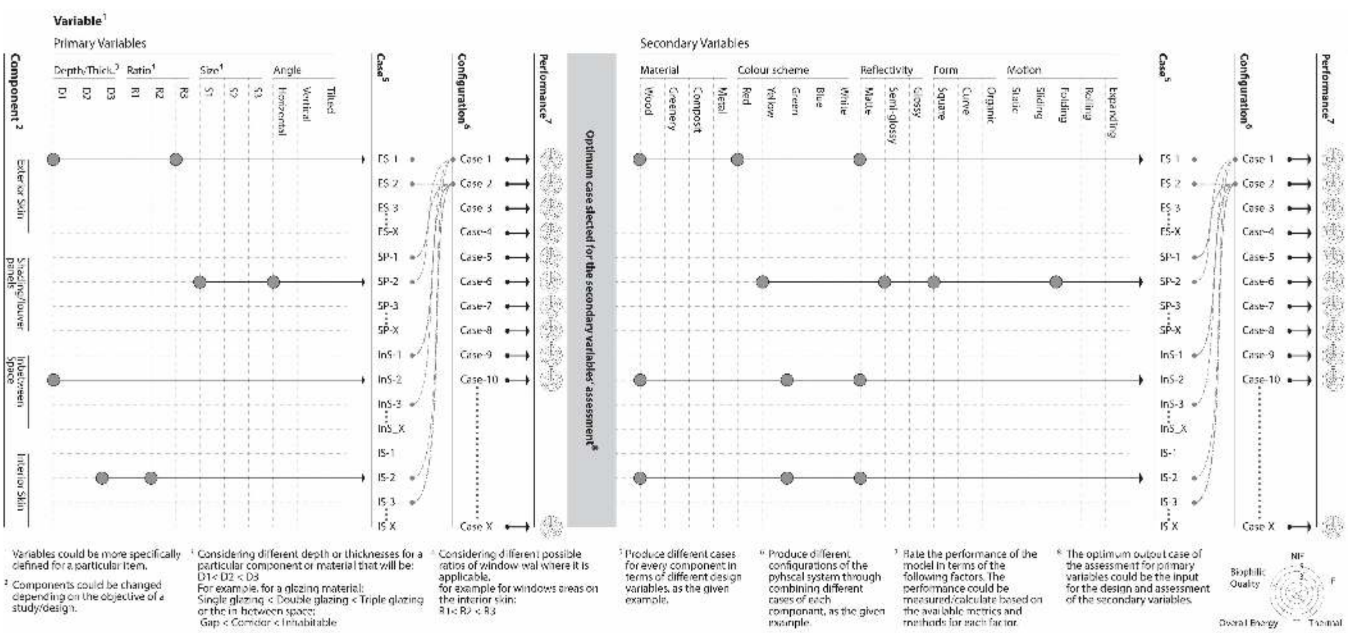


Figure 11. Primary and secondary design variables for the parametric study of ABFs' physical components in terms of photobiological, thermal, biophilic and energy factors

Conclusion

This research discussed the application of ABFs that could potentially improve indoor environmental quality and promote human-nature relations in Northern Canada where non-adapted buildings have been severely disconnected occupants from the climate without considering their photobiological and biophilic needs. The deficiencies of existing buildings in Northern Canada were studied. The paper also showed that existing ABFs require further developments to deal with the challenging natural lighting and thermal conditions and respond to northern occupants' photobiological and biophilic needs. The study identified four particular areas of inquiry that should be further investigated for the integrated development of ABFs: (i) the physical structure and configuration of components (ii) the design of solar shading/louver panels to address photobiological needs, biophilic requirements and energy issues (iii) the development of lighting adaptation scenarios responding to biophilic, photobiological and thermal needs, local photoperiods and energy issues, and (iv) the overall biophilic quality with a special focus on promoting indoor-outdoor relationships. The research then focused on the integrated dimension of ABFs and proposed a fundamental framework to design and optimize for biophilic, photobiological, thermal and energy requirements. The ABFs' framework was devised and explained in three fundamental phases namely (1) process environmental data (2) process adaptation scenarios, and (3) operate adaptation scenarios. The paper explained all phases and issues that need to be addressed in future studies. In particular, the development of lighting and thermal adaptation scenarios is at the core of ABFs demanding special attention. Lighting metrics and scenarios must be further developed to establish hourly/daily/seasonally indoor lighting patterns with respect to IF and NIF effects, occupants' behaviour, building classes, activities, local photoperiods, thermal and energy issues. Furthermore, primary and secondary components' configurations and design variables of multi-skin systems were discussed in order to be parametrically studied and optimized in terms of the performance indicators. The components should also be designed with respect to severe climatic conditions of extreme cold climates associating with extensive freezing and heavy snow accumulation. Future research could use the proposed framework and parametric method to develop biophilic, photobiological and energy efficient ABFs for healthy buildings in Northern Canada and improve human-nature relationships in such regions.

Authors' contribution

This paper is extracted from a doctoral research done by the first author, Mojtaba Parsaee. The rest of the authors are the co-supervisor of the research. As the research is interdisciplinary, each author contributes to different parts of the paper. Claude Demers supervised the architectural part. Mar Hebert supervised the biological part. Jean-Francois Lalonde supervised the lighting capture and sensory environment developments. Andre Potvin supervised the energy efficiency issues. You can read more about the overall research at this link: (https://sentinellenord.ulaval.ca/en/research/optimizing-biophilia-extreme-climates-through-architecture).

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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Appendix A

The sources of information for Table 1 and photo courtesies of Figure 3

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21	https://www.stylepark.com/en/news/the-mutable-house	© https://www.stylepark.com/en/news/the-mutable-house
22	https://www.archilovers.com/projects/203971?utm_source=lov&utm_medium=email&utm_campaign=lov_news#info	© David Boureau on https://www.v2com-newswire.com/fr/salle-de-presse/dossiers-de-presse/1008-06/logements-sociaux-rue-castagnary#
23	https://www.domusweb.it/en/architecture/2014/03/07/music_conservatory.html	© Sergio Grazia on https://www.domusweb.it/en/architecture/2014/03/07/music_conservatory.html
24	https://www.archdaily.com/406718/institut-des-sciences-analytiques-parc-architectes	© Sébastien Morel on https://www.archdaily.com/406718/institut-des-sciences-analytiques-parc-architectes
25	https://www.archdaily.com/326747/q1-thyssenkrupp-quarter-essen-jswd-architekten-chaix-morel-et-associes	© Michael Wolff on https://www.archdaily.com/326747/q1-thyssenkrupp-quarter-essen-jswd-architekten-chaix-morel-et-associes
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28	https://www.archdaily.com/41775/lofts-cherokee-studios-pugh-scarpa	© Brooks + Scarpa on https://www.archdaily.com.br/br/868074/aia-anuncia-vencedores-dos-premios-thomas-jefferson-e-de-realizacao-colaborativa
29	https://www.architonic.com/en/project/sefar-swiss-railway-main-office-building/5102419 https://www.stylepark.com/de/news/wie-aus-metall-und-glas-zugleich	© Colt on https://www.stylepark.com/de/news/wie-aus-metall-und-glas-zugleich
30	https://www.archdaily.com/522344/sharifi-ha-house-nextoffice	© Nextoffice on https://www.archdaily.com/522344/sharifi-ha-house-nextoffice

Appendix B

Part 1. Some examples of thermal comfort indicators: PMV (Predicted Mean Vote)[14], PET (Physiological Equivalent Temperature)[140], UTCI (Universal Thermal Climate Index)[141] and SET*/OUT_SET* (Standard Effective Temperature/ Outdoor Standard Effective Temperature)[142].

Part 2. The following table shows parameters and metrics to capture and to analyse IF and NIF effects of lighting and daylighting in buildings.

Target analysis	**Metric and parameter**	**Sample study**	**Tools and methods**
Image forming (IF) effects	Luminance ratio and distribution	Maskarenj et al. [143], Inanici [144], Inanici and Hashemloo [145]	Digital lux meter, Light Dependent Resistor (LDR) sensors, and High Dynamic Range (HDR) images taken by a digital camera

	Illuminance level, distribution and uniformity	Chraibi et al. [146]	Photometer sensors
	Colour temperature, colour rendering and appearance	Aste et al. [147]	Photometer sensors Spectrophotometer
	Directionality of light	Cantin and Dubois [148]	Simulation
Non-image-forming (NIF) effects	Circadian Light (CL_A) and Circadian Stimulus (CS)	Acosta et al. [149]	Spectrophotometer Simulation
	Equivalent Melanopic Lux (EML)	Konis [150], Jung [151], Jung and Inanici [152]	A digital Charge Coupled Device (CCD) spectrometer and HDR images taken by a digital camera
	Circadian Effect Thresholds	Amundadottir et al. [153]	Spectrophotometer
	Melanopic-Photopic ratio (M/P)	Berman and Clear [30]	Spectrophotometer
Daylighting	Daylight Factor (DF)	Lim et al. [154]	ENMARS TM-203 illuminance loggers
	Daylight Autonomy (DA)	Bian and Ma [155]	The arrangement of photometric sensors to capture illuminance
	Useful Daylight Illuminance (UDI)	Nabil and Mardaljevic [156]	Simulation
	Daylight Coefficient (DC)	Yoon et al. [157]	Photometric sensors to capture illuminance
	Daylight Glare Probability (DGP3)	Konstantzos et al. [158]	HDR images taken by a digital camera
	Daylight Glare Index (DGI) or Cornell Equation metric	Hirning et al. [159]	HDR images taken by a digital camera

Part 3. A list of references discussing advancements and challenges in the field of occupancy detection and control systems as well as data mining and machine learning techniques for detecting and predicting occupants' behaviour: Hong et al. [107], Parsaee et al. [116], Trivedi and Badarla [160], Heidari Matin and Eydgahi [161, 162], Al-Masrani and Al-Obaidi [163], Konstantoglou and Tsangrassoulis [164], Delzendeh et al. [165], Ashouri et al. [166], Miller et al. [167], Fan et al. [168], Hong et al. [169]

Part 4. Some example studies of multi-objective optimization of façade's design: Buratti et al. [170], Oral et al. [171], Shahbazi et al. [172], Lartigue et al. [173], Goia et al. [174], Ferrara et al. [175], Zhai et al. [176], Yi [177]

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