Biophilic and photobiological developments of adaptive high-performance building envelopes for Northern Canada

Thèse

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Résumé

Les configurations des enveloppes et des fenêtres des bâtiments nordiques doivent répondre aux exigences du bien-être photobiologique et psychologique des occupants par des relations positives efficaces avec la nature subarctique. Les enveloppes de bâtiments existant dans les climats (sub)arctiques du nord du Canada n'ont pas encore permis d'établir des connexions efficaces entre l'intérieur et l'extérieur afin d'aborder les relations positives entre les humains et la nature et le bien-être photobiologique et psychologique. Des connexions intérieures-extérieures efficaces indiquent une connectivité optimale de l'intérieur avec la nature subarctique extérieure répondant au bien-être des occupants et aux besoins énergétiques. Les relations positives des occupants avec la nature subarctique correspondent à des avantages maximums et des risques minimums des climats nordiques extrêmes pour le bien-être photobiologique-psychologique.

L'objectif général de cette thèse est de favoriser les relations positives des occupants avec la nature subarctique au moyen de connexions efficaces entre l'intérieur et l'extérieur qui pourraient répondre aux facteurs de bien-être biophiliques et photobiologiques liés à la lumière du jour et aux photopériodes. Dans ce but, un modèle fondamental d'enveloppe de bâtiment adaptative à haute performance est développé comme une solution architecturale qui pourrait optimiser les connexions intérieur-extérieur et les principaux indicateurs biophiliques et photobiologiques. La thèse visait spécifiquement à articuler une approche photobiologique du design biophilique dans les climats nordiques extrêmes qui permet d'établir un cadre conceptuel et de design pour développer des enveloppes de bâtiments. La thèse visait également à identifier les lacunes des enveloppes de bâtiment existantes dans le Grand Nord du Canada ainsi que des systèmes d'enveloppes adaptatives existants en termes d'indicateurs biophysiques-photobiologiques. Les principaux éléments architecturaux des enveloppes adaptatives, notamment la configuration des fenêtres et les caractéristiques de surface des systèmes d'ombrage, en particulier la couleur et la réflectance, sont étudiés pour répondre aux besoins biophiles-photobiologiques des occupants du Nord.

Les méthodologies de la thèse comprennent une revue de la littérature pour discuter des directives récentes de design biophilique, de l'éclairage photobiologique et des études de connectivité avec la nature par rapport aux climats subarctiques, en particulier la lumière du jour et les photopériodes. Des méthodes numériques et expérimentales ont été intégrées pour évaluer les performances biophiliques, d'éclairage photobiologique, thermiques et énergétiques des systèmes d'enveloppe pour une étude de cas d'un bureau open-plan dans le nord du Canada. Des méthodes expérimentales avec des modèles à l'échelle physique, des images à haute gamme dynamique et des techniques de post-traitement ont été utilisées pour capturer, calculer et visualiser les paramètres d'éclairage photobiologique. L'impact des caractéristiques des panneaux d'ombrage (SP) sur les performances d'éclairage photobiologique a été étudié par l'expérimentation d'environ 40 prototypes à l'échelle 1:50 et 23 prototypes à l'échelle 1:10 sous un ciel dégagé/couvert avec un éclairage naturel réel/artificiel. Des modèles numériques ont été développés pour évaluer les caractéristiques biophiques et thermiques/énergétiques des systèmes d'enveloppe.

Les résultats de la thèse comprennent un cadre théorico-conceptuel du design photobiologique - biophilique qui identifie les relations positives des occupants avec la nature subarctique à travers les enveloppes. Des scénarios d'adaptation de l'éclairage photobiologique intégrés aux exigences thermiques ont été élaborés, qui permettent de répondre aux besoins photobiologiques horaires/saisonniers des occupants du Nord dans des bâtiments différents. Les lacunes des enveloppes à une peau typique du Nord du Canada et des enveloppes à plusieurs peaux avec des profondeurs d'espaces intermédiaires/cavités et des tailles de fenêtre différentes ont été spécifiquement évaluées en termes des indicateurs biophiliques, photobiologiques et thermiques. Un modèle fondamental d'enveloppes adaptatives à haute performance est proposé pour les bâtiments du Nord, qui comprend une taille de fenêtre optimale, un système d'ombrage dynamique coloré et isolé, et un système de buffer thermique constitué d'une peau extérieure en verre. Les performances d'éclairage photobiologique des configurations des SP, incluant la couleur, la réflectance, l'orientation, l'inclinaison, la densité, la taille, l'ouverture et la position à la fenêtre, ont été caractérisées. Les résultats des élévations expérimentales/numériques montrent que l'enveloppe adaptative proposée pourrait offrir des connexions intérieures-extérieures efficaces qui répondent aux besoins photobiologiques-psychologiques et aux exigences énergétiques des occupants du Nord. Les résultats de la thèse pourraient informer les architectes et les responsables politiques sur les possibilités que les enveloppes adaptatives et les cadres photobiologiques-biophiles offrent pour améliorer le bien-être du public et l'efficacité énergétique dans les climats nordiques. Les principaux enjeux des futurs développements des bâtiments biophiliques adaptatifs dans les climats nordiques ont également été soulignés, notamment en matière d'analyses du cycle de vie et d'études socioculturelles.

Abstract

Sub-Arctic building envelope configurations must address occupants' photobiological-psychological wellbeing through positive relationships with the outdoor sub-Arctic nature. Existing building envelopes in Northern Canada's (sub-)Arctic climates have not, yet, enabled efficient indoor-outdoor connections to address positive human-nature relationships and photobiological-psychological wellbeing. Efficient indoor-outdoor connections indicate optimum connectivity of indoors with Northern climates in terms of occupants' wellbeing and energy factors. Positive occupants' relationships with the sub-Arctic nature refer to maximum benefits and minimum risks of the extreme cold weather and strong photoperiod of Northern climates for photo-biological and psychological wellbeing.

The general objective of this dissertation is to foster positive occupants' relationships with sub-Arctic nature by enabling efficient indoor-outdoor connections which could respond to biophilic and photobiological wellbeing factors related to daylighting and photoperiods. To this end, a fundamental model of adaptive high-performance building envelopes is developed as an architectural solution which could optimize indoor-outdoor connections and main biophilic and photobiological indicators. The dissertation specifically aimed at articulating a photobiological approach to biophilic design in extreme Northern climates which enables establishing a conceptual and design framework to develop building envelopes. The thesis also focused on identifying the shortcomings of existing Canadian Northern building envelopes as well as existing adaptive envelope systems in terms of biophilic-photobiological indicators. Main architectural elements of adaptive envelopes including window configuration and surface characteristics of shading systems, in particular color and reflectance, are explored to respond to Northern occupants' biophilic-photobiological needs.

The thesis methodologies include a scoping literature review to critically discuss recent biophilic design guidelines, photobiological lighting, and nature connectedness/relatedness studies in relation to sub-Arctic climates, especially daylighting and photoperiods. Numerical and experimental methods were integrated to evaluate biophilic, photobiological lighting, thermal and energy performance of envelope systems for a case study of an open-plan office in Northern Canada. Experimental methods with physical scale models, high dynamic range imagery and post-processing techniques were employed to capture, compute, and visualize photobiological lighting parameters. Impacts of shading panels' (SPs) characteristics on photobiological lighting performance were explored by experimenting approximately 40 1:50-scale prototypes and 23 1:10-scale prototypes under clear/overcast skies with actual/artificial daylighting. Numerical models were developed to evaluate biophilic and thermal/energy performance of envelope systems.

Dissertation outcomes include a theoretical-conceptual framework of photobiological-biophilic design which characterizes positive occupants' relationships with the sub-Arctic nature through envelopes. Photobiological lighting adaptation scenarios integrated with thermal requirements were developed which could address hourly/seasonal photobiological needs of Northern occupants in different buildings. Deficiencies of typical single-skin envelopes in Northern Canada and multi-skin envelopes with different depths of intermediate spaces/cavities and window sizes were specifically evaluated in terms of biophilic, photobiological lighting and thermal indicators. A fundamental model of adaptive high-performance envelopes is proposed for Northern buildings which includes an optimum window size, a dynamic-colored-insulated shading system, and a thermal buffer system made of a glazing exterior skin. Photobiological lighting performance of SPs' configurations, including color, reflectance, orientation, inclination, density, size, openness, and position at the window, were characterized. Results of experimental-numerical elevations reveal that the proposed adaptive envelope could offer efficient indoor-outdoor connections which respond to Northern occupants' photobiological-psychological needs and energy requirements. Dissertation outcomes could enlighten architects and policymakers about potentials of adaptive envelopes and integrative photobiological-biophilic frameworks to improve public wellbeing and energy efficiency in Northern climates. Major issues for future developments of adaptive biophilic buildings in Northern climates were also outlined including life cycle assessments and sociocultural studies.

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ABF	Adaptive building façade
AS	Artificial sky
CBT	Core body temperature
CCT	Correlated color temperature
CDD	Cooling degree day
CIE	Commission internationale de l'éclairage
CMF	Color matching functions
DS	Direct sunlight
EM	Equivalent melanopic
EV	Exposure value
FDWR	Fenestration-and-door-to-wall ratio
FOV	Field of view
HDR	High dynamic range
h	Horizontal
HDD	Heating degree day
h-FOV	Horizontal field of view
IF	Image forming
ipRGCs	intrinsically photosensitive retinal ganglion cells
L	Light (for color's saturation)
Lat	Latitude
LDR	Low dynamic range
Lon	Longitude
M/P	Melanopic/Photopic
mRGCs	Melanopsin-expressing retinal ganglion cells
MSF	Multi-skin façade
NIF	Non-image forming
RGB	Red-Green-Blue
S	Strong (for color's saturation)
SAD	Seasonal affective disorder
SHGC	Solar Heat Gain Coefficient
SP	Shading panel
SPD	Spectral power distribution

SSH	Secure shell
SV	Specularity value
TCS	Test color sample
v	Vertical
v-FOV	Vertical field of view
VT	Visual transmittance
WHR	window-to-wall-height ratio
WLR	window-to-wall-length ratio
WWR	Window-to-wall ratio
XYZ	CIE tristimulus values
Y	Yellow (for color’s hue like yellow-green color)

To my parents, Ali and Zeinab,
for their unconditional love and support

"The fact is that the difference between a good building and a bad building, between a good town and a bad town, is an objective matter. It is the difference between health and sickness, wholeness and dividedness, self-maintenance and self-destruction. In a world which is healthy, whole, alive, and self-maintaining, people themselves can be alive and self-creating. In a world which is unwhole and self-destroying, people cannot be alive: they will inevitably themselves be self-destroying, and miserable."

- Christopher Alexander
The timeless way of Building (page 25)

"Despite the great progress made in many sciences and humanities, the concept of process has not yet become a normal part of the way we think about architecture… Our current view of architecture rests on too little awareness of becoming as the most essential feature of the building process. Architects are much too concerned with the design of the world (its static structure), and not yet concerned enough with the design of the generative processes that create the world (its dynamic structure)."

- Christopher Alexander
The nature of order (page 4)

Remerciements

This dissertation would not have been possible without the contribution and support of many people who encouraged and helped me in different ways.

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Last but not least, my deepest gratitude goes to my family, especially my parents Ali Parsaee and Zeinab Keshtkar, for their love and support throughout my life. Without their encouragement, patience, and inspiration, I would not have been able to pursue my academic and life goals.

Avant-propos

This dissertation includes an introduction and four chapters followed by conclusions and two annexes which report the research and development process of biophilic photobiological high-performance adaptive envelopes for Northern Canada. The following Figure AP-1 shows the general structure and narrative of the thesis. The instruction highlights major issues and research problems, general and specific objectives, and methodological approaches of each chapter. The introduction also presents a brief discussion of each chapter which provides a comprehensive overview of the thesis design and process. Important contributions and major limitations of the thesis are also presented in the instructions as expected items of the thesis. As displayed in Figure AP.1, Chapter 1 and annex 1 discuss a theoretical and conceptual framework of the research in terms of biophilia and photobiological lighting features in relation to northern climates, daylighting, and photoperiods. Chapter 2 and annex 2 establish a design framework of adaptive envelope systems to respond to biophilic and photobiological needs of northern occupants. Chapter 2 and annex 2 also discuss impacts of existing northern building envelopes as well as adaptive envelope systems on biophilic and photobiological requirements of northern occupants. Chapter 3 presents a benchmarking study and develops an experimental methodology to capture and visualize photobiological lighting factors in architectural models by using raspberry Pi cameras. In Chapter 4, a fundamental model of biophilic-photobiological adaptive envelopes for Northern buildings is proposed and evaluated by using experimental and numerical methods. A conclusion chapter of the thesis concludes the main contributions and outcomes of the entire thesis. The conclusion chapter also presents limitations of the research and outlines issues for future studies and development.

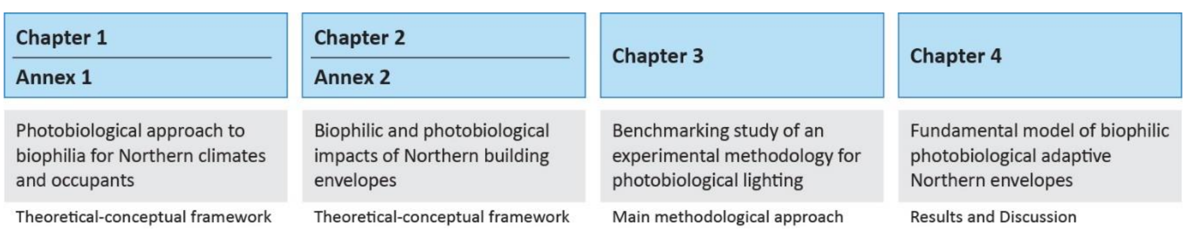

Figure AP. 1. Thesis structure and research design

This is a paper-based thesis format. Chapters 1-3 have already been published as scientific papers in different peer-reviewed international journals. Chapter 4 has been submitted and under reviewed. Annexes A1 and A2 have been presented and published in the conference proceedings as given in the following bibliography. Each chapter and annex have a specific instructions and literature review to provide a background and theoretical framework of the research published as a scientific paper. Hence, some of the literature and theoretical concepts are overlapped and repeated in different chapters or annexes. Some of the chapters and annexes were published before the thesis was deposited. Thus, some of the figures and items were revised to use in the thesis based on the comments of the thesis jury, which are highlighted as footnotes in the thesis.

I, Mojtaba Parsaee, have written and submitted all papers identified as the first and corresponding author. Each co-author has contributed to different parts of the publications. Claude MH Demers has been the principal supervisor of the thesis who supervised architectural aspects related to lighting and biophilia in extreme climates. Claude has also proofread and checked the overall consistency of discussions in the papers and the thesis. Marc Hébert has co-supervised the biological aspects and reviewed the accuracy of biological discussions in the publications and the thesis. Jean-Francois Lalonde has co-supervised lighting measurements and HDR imagery and post-processing techniques as well as the overall contributions of the thesis. André Potvin has collaborated in the architectural and engineering aspects related to energy issues and building physics. In chapters 3 and 4, Mehlika Inanici, professor at Washington University, Seattle, US, has collaborated to calibrate the camera measurements and developed the HDR images' post-processing techniques to compute photobiological lighting parameters. Mehlika's collaborations were acknowledged as a co-author in respective publications extracted from chapters 3 and 4. The support of the sentinel North program of Université Laval, funding from the Canada First Research Excellence Fund, were acknowledged in all publications as made this doctoral research possible. The bibliography of publications is as the following. The references and bibliographies of all chapters are updated, unified, and presented as a whole at the end of the dissertation.

- **Chapter 1:** M. Parsaee, C. M. Demers, M. Hébert, J.-F. Lalonde, and A. Potvin, "A photobiological approach to biophilic design in extreme climates". *Building and Environment,* vol. 154, pp. 211-226, 2019.
- **Chapter 2:** M. Parsaee, C. M. Demers, M. Hébert, J.-F. Lalonde, and A. Potvin, "Biophilic, photobiological and energy-efficient design framework of adaptive building façades for Northern Canada". *Indoor and Built Environment,* Published online February 2020.
- **Chapter 3:** M. Parsaee, C. M. Demers, J.-F. Lalonde, A. Potvin, M. Inanici, and M. Hébert, "Human-centric lighting performance of shading panels in architecture: a benchmarking study with lab scale physical models under real skies". *Solar Energy,* vol. 204, pp. 354-368, 2020.

- **Chapter 4:** M. Parsaee, C. M. Demers, A. Potvin, J.-F. Lalonde, M. Inanici, and M. Hébert, "Coexist harmoniously with extreme climates: "Biophilic photobiological adaptive envelope for sub-Arctic Buildings". *Solar Energy.* Submitted and under reviewed, November 2020.
- **Annex A1**: M. Parsaee, C. M. Demers, M. Hébert, J.-F. Lalonde, and A. Potvin, "Photobiological climate-based lighting adaptation scenarios for high-performance biophilic buildings," in *35th PLEA Conference: Sustainable Architecture and Urban Design*, *Planning Post Carbon Cities*, A Coruña, Spain, September 1-3, 2020.
- **Annex A2**: M. Parsaee, C. M. Demers, M. Hébert, J.-F. Lalonde, and A. Potvin, "Single-skin and multi-skin building envelopes in extreme sub-Arctic climates: biophilic, healthy lighting and thermal performance evaluations" in *35th PLEA Conference: Sustainable Architecture and Urban Design*, *Planning Post Carbon Cities*, A Coruña, Spain, September 1-3, 2020.

Introduction

This dissertation develops adaptive high-performance envelopes based on biophilic and photobiological indicators for Northern buildings, as an architectural solution which could foster positive relationships among occupants and sub-Arctic climates by establishing efficient indoors' connections with outdoors, especially daylighting and photoperiods. Envelope configurations and openings play key roles in connecting indoors to outdoor sub-Arctic climates. Indoor-outdoor connections through envelopes affect occupants' wellbeing needs related to biophilic, lighting, and thermal performance of buildings. Northern Canada's building practices and envelope configurations have not yet provided occupants with efficient indoor-outdoor connections which could address photobiological-psychological needs combined with energy requirements. The main objective of this dissertation is, hence, focused on developing Northern building envelopes to offer positive relationships among occupants and the outdoor sub-Arctic nature, especially daylighting and photoperiods, in terms of biophilic and photobiological indicators. Specific objectives, hypotheses and methodologies of dissertation chapters are summarized in Table Int.1. As shown in the table, the dissertation reports the research and development process in four chapters and two annexes. A theoretical framework of positive occupants' relationships with sub-Arctic climates is established in Chapter 1 through integrating photobiological factors with biophilic design which enabled synthesizing lighting adaptation scenarios for building envelopes, as further presented in Annex A1. The biophilic-photobiological theoretical framework is used to develop an integrative architectural design framework of adaptive envelope systems as discussed in Chapter 2 and Annex A2. The integrative architectural framework enabled evaluating and optimizing biophilic, photobiological, thermal performance of adaptive envelope systems for Northern buildings in relation to occupants' wellbeing and energy requirements. Photobiological lighting performance of shading panels' characteristics were, particularly, studied in Chapter 3. Shading panels are the key element of adaptive envelope system which could optimize occupants' connections with extreme sub-Arctic daylighting and photoperiods. The fundamental model of biophilic adaptive high-performance envelopes for Northern buildings is proposed in Chapter 4. The proposed adaptive model could foster positive occupants-naturel relationships by providing efficient indoor-outdoor connections and optimizing biophilic, healthy lighting, thermal and energy performance indicators. The research employed several methodologies to establish the theoretical and architectural frameworks and to develop adaptive envelope models based on biophilic and photobiological indicators for Northern Buildings. Scoping reviews of recent biophilic, Nature connectedness/relatedness and photobiological studies as well as adaptive envelope systems were performed to constitute the biophilic-photobiological theoretical and architectural design frameworks. Experimental methods with physical scale models, high dynamic range (HDR) imagery and post-processing techniques were developed to evaluate photobiological lighting performance in architectural models. Numerical methods were used to evaluate biophilic and thermal/energy performance of envelopes. The conclusion chapter of the dissertation presents the outcomes and contributions of the research which could enlighten architects, lighting designers and policymakers for buildings and developments in Northern climates. Outlines for future developments and studies are also discussed in terms of technical, economic, and sociocultural aspects.

Table Int. 1. Summary of main objectives, hypotheses, and methodologies articulated for the dissertation and each chapter

Dissertation (overall)		
Main objective	**Main hypothesis**	**Methodological approach**
• Foster positive relationships among occupants and sub-Arctic climates by establishing efficient indoor-outdoor connections offered by Northern building envelopes in terms of photobiological-psychological wellbeing and energy requirements with respect to daylighting and seasonal photoperiods	• Developing adaptive high-performance envelopes based on biophilic and photobiological indicators for Northern buildings could enable efficient indoor-outdoor connections responding to wellbeing and energy requirements in positive relationships with sub-Arctic climates.	• Integrated approaches including scoping literature review, and experimental and numerical methods
Chapter 1		
Main objectives	**Main hypotheses**	**Methodology**
• Characterize biophilic design and photobiological indicators in relation to humans' photobiological-psychological needs in sub-Arctic climates • Establish main parameters and criteria for photobiological lighting design in relation to biophilia and building envelopes, and Northern daylighting	• Biophilic and photobiological features could define positive human-nature relationships in Northern climates. • Biophilic design has limits and potentials for effective applications in Northern climates. • Biophilic features have not yet integrated with photobiological requirements in Northern climates.	• Scoping literature review
Chapter 2		
Main and specific objectives	**Main and specific hypotheses**	**Methodologies**
• Characterize performance of existing Canadian northern building envelopes and existing adaptive envelope practices in terms of biophilic and photobiological lighting factors • Develop a design framework to optimize adaptive envelope variables for biophilic and photobiological requirements under Northern conditions • Characterize lighting adaptation scenarios integrated with thermal requirements in Northern climates	• Northern building envelopes' configurations and openings must respond to biophilic and photobiological needs in addition to energy factors. • Existing adaptive envelope practices have not considered photobiological needs and seasonal photoperiods, especially for potential applications in Northern climates. • A fundamental design framework is required to incorporate biophilic and photobiological factors with adaptive envelope configurations.	• Scoping literature review • Case study analysis of adaptive envelope practices

Chapter 3		
Main and specific objectives	**Main and specific hypotheses**	**Methodologies**
• Explore photobiological lighting performance of shading panels' (SPs) characteristics, particularly color, reflectance, orientation, and openness. • Explore potential adjustments of SPs' characteristics to photobiological lighting adaptation scenarios under Northern conditions • Establish an experimental procedure to visualize photobiological lighting parameters in architectural models through high dynamic range (HDR) imagery and post processing techniques	• SPs' surface characteristics, including color, reflectance, orientation, and openness, could modify daylighting spectrums corresponding to photopic and melanopic units and correlated color temperature (CCT). • SPs with cool color could increase melanopic units and CCT in the space whereas warm color panels could increase photopic units and reduce CCT in the space. • Visualization methods with scale models could improve the understanding of photobiological lighting design during early stages.	• Experimental methods for biophilic, healthy lighting, thermal and energy performance evolutions
Chapter 4		
Main and specific objectives	**Main and specific hypotheses**	**Methodologies**
• Develop a fundamental model of adaptive high-performance envelopes for Northern buildings based on biophilic-photobiological indicators and energy factors • Optimize the opening size for efficient biophilic connections with outdoors • Adjust SPs design variables to hourly photobiological, biophilic and thermal requirnemts in Northern climates	• A fundamental model of adaptive envelopes could be developed based on biophilic and photobiological indicator and energy factors to improve Northern building performance and respond to occupants' photobiological-psychological wellbeing. • Window sizes, SPs' characteristics and intermediates spaces/cavities are key elements of adaptive envelopes which could optimize biophilic, photobiological and thermal factors in Northern buildings.	• Scoping literature review • Experimental, numerical, and analytical methods for integrative biophilic, healthy lighting, thermal and energy performance evolutions
Annex A1		
Main objectives	**Main hypotheses**	**Methodologies**
• Develop climate-based lighting adaptation scenarios for proper hourly/seasonal photobiological responses based on the synthesised factors and criteria in chapter 1 for different buildings uses, such as office, educational, residential and health care, under northern daylighting and seasonal photoperiods	• Lighting adaptation scenarios are required to present hurly/seasonal protocols and patterns for adjusting indoor lighting parameters to occupants' photobiological needs in relation to daylighting availability and seasonal photoperiods. • Lighting adaptation scenarios could be adjusted for different building uses and local photoperiods.	• Scoping literature review
Annex A2		
Main objectives	**Main hypotheses**	**Methodologies**
• Explore the potentials and shortcomings of single-skin envelopes, representing existing Northern buildings, and multi-skin envelopes with different window sizes in terms of biophilic, healthy lighting, thermal and energy indicators under Northern climatic conditions	• Single-skin envelopes with a low opening size as existing Northern buildings could not respond to biophilic and photobiological needs. • Multi-skin envelopes with a high opening size could improve biophilic, photobiological, thermal and energy performance of Northern buildings.	• Numerical and experimental methods for biophilic, healthy lighting, thermal and energy performance evolutions

The dissertation articulates efficient indoor-outdoor connections through envelopes as optimum connectivity of interior spaces with extreme Northern conditions which could respond to occupants' wellbeing needs combined with energy efficiency requirements. Positive occupants-nature relationships are identified as maximum benefits and minimum risks of sub-Arctic nature for photobiological and psychological wellbeing. Extreme Northern climates, i.e., near and above 50° N of Canada towards the Arctic, could negatively impact occupants' wellbeing, especially in terms of photobiological disorders related to local daylighting availability and strong seasonal photoperiods. The extreme cold weather for several months of the year, also, limits adequate outdoor activities and exposure to daylighting. Biophilia, the idea of connections with natural systems, could promote Such psychological wellbeing [1-5] in terms of the reduction of stress and anxiety [6-8], decrease of boredom, irritation and fatigue [1, 9], improvements of mental and cognitive performance, positive emotions and moods [10, 11]. Photobiological wellbeing requires proper natural/artificial lighting qualities at the proper time of the day [12] followed by sufficient darkness at nights which could regulate internal body clocks or circadian systems, wake-sleep cycles, alertness, and mood [13]. Prioritizing and maximizing the use of daylighting and accessibility to natural photoperiods in buildings are, hence, strongly recommended because of several positive effects on photobiological-psychological wellbeing [1, 3, 12, 14]. Yet, drastic seasonal photoperiods of Northern climates create long summer days and short winter days which could not generally adjust typical humans' circadian clocks and regulate biological days and nights, as illustrated in Figure Int.1. As presented in the following chapters, this thesis formulates biophilic and photobiological indicators in relationships to Northern building envelopes in order to foster positive occupant-nature relationships through efficient connections among indoors and the outdoor sub-Arctic climate.

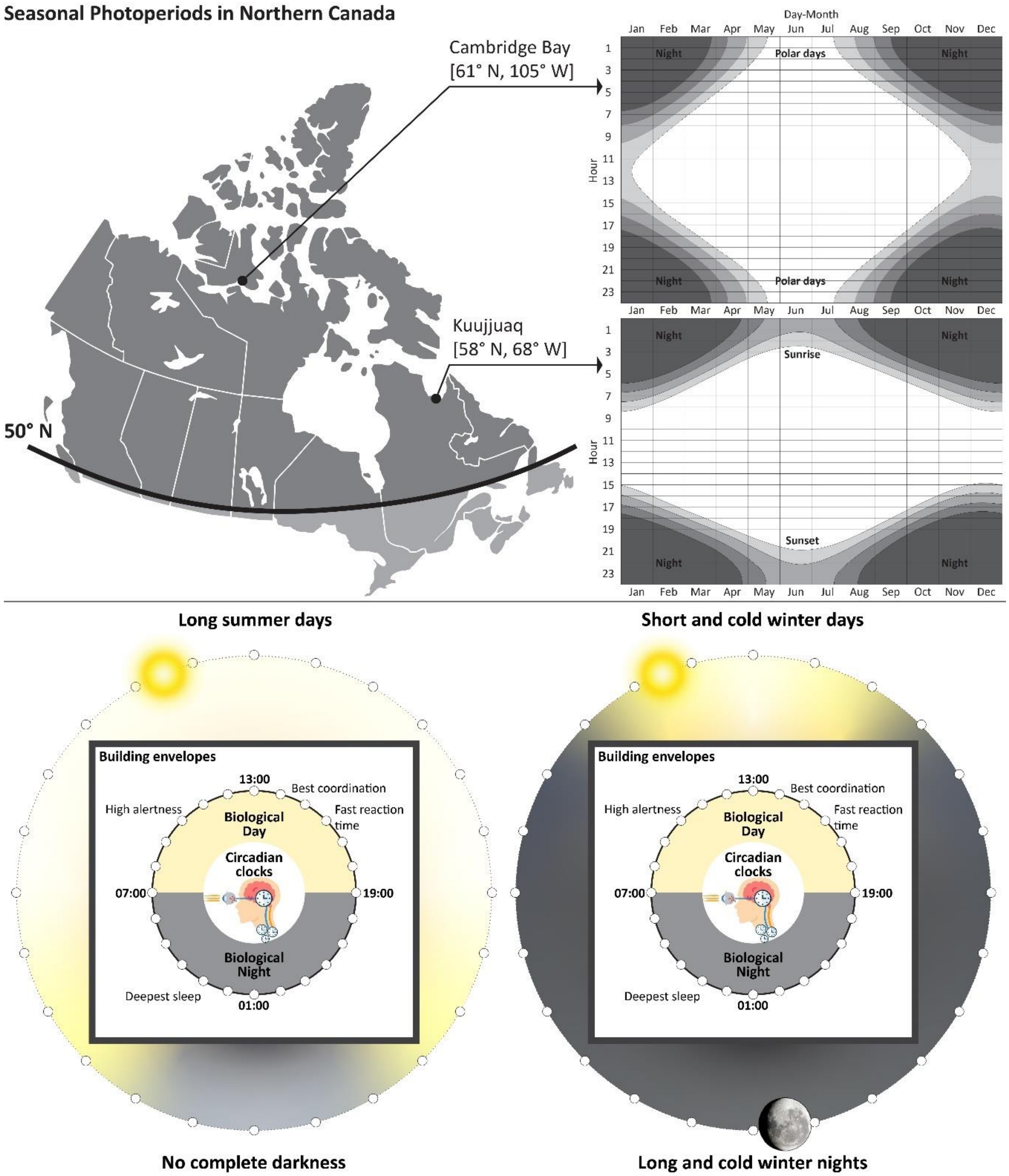

Figure Int. 1. (a) Northern Canada and local seasonal photoperiods; (b) Typical building occupants' circadian clocks and biological day/night cycles vs. typical summer/winter days in Northern Canada.

Perspective on Chapter 1

Chapter 1 aims at developing a photobiological approach to biophilic design in extreme Northern climates by discussing occupants' relationships with sub-Arctic nature in terms of biophilic features, photobiological effects and climatic conditions. A scoping literature review was conducted to critically discuss the theory of biophilia and the concept of biophilic design in relation to photobiological needs of people and extreme Northern climatic conditions, particularly in terms of daylighting and seasonal photoperiods. Connections with natural phenomena, which exist outside buildings and enclosures, are acknowledged as the core of biophilia and biophilic design. Mimicking natural patterns and connections with naturalistic features inside the space are, also, considered as biophilic features which could produce positive wellbeing effects. In chapter 1, principles of biophilic design are synthesized in relation to building envelopes and climate classifications. The scoping review enabled discussing the structural deficiencies of biophilic design to effectively incorporate in the architectural design process and to implement in extreme Northern conditions.

Chapter 1 also brings particular attention to shortcomings of biophilic design in relation to daylighting availability and strong seasonal photoperiod in Northern climates which could negatively affect photobiological wellbeing of occupants. Humans' photobiological responses are defined in terms of image forming (IF) and non-image forming (NIF) effects of light after reaching eyes' photoreceptors. IF effects are related to vision and formation of images in the brain. NIF effects are referred to impacts of light on circadian clocks, sleep/wake cycles, alertness, and mood. The literature review indicates health problems and disorders related to NIF effects of lighting and extreme seasonal photoperiods, such as desynchronized circadian clocks and sleep disorders, which are commonly reported in sub-Arctic climates. The human-centric lighting design, photobiological or healthy lighting approach is recognized as considering IF and NIF effects in the lighting and architectural design of buildings. Recent research on humans' photobiological needs and human-centric lighting was studied through the scoping review to determine the main parameters, factors, and thresholds to address building occupants' lighting needs for different activities during the day. The outcomes of the scoping review enabled establishing lighting criteria and patterns to respond to hourly photobiological needs of occupants for different activities in buildings.

Hourly/seasonal photobiological climate-based lighting adaptation scenarios were developed for different building uses in Northern Canada based on the extracted photobiological criteria, as presented in Annex A1. Lighting adaptation scenarios offer patterns and protocols to adjust main lighting parameters to occupants' needs in buildings. Maximizing the use of daylighting, as a biophilic feature, is prioritized in the developed climate-based lighting adaptation scenarios. Annex A1 presents different lighting adaptation scenarios which are developed for hourly/seasonal photobiological needs of occupants in typical office, educational, residential and health care buildings in relation to daily/seasonal daylighting availability and local photoperiods in a Canadian Northern city, as an example. The conclusions of Chapter 1 and Annex A1 outline major aspects for future developments of biophilic design in relation to photobiological needs and Northern climates. The conclusions, specifically, call for attention to adaptive envelope systems as a plausible architectural hypothesis which could optimize biophilic design qualities and respond to photobiological needs of occupants under Northern climatic conditions.

Perspective on Chapter 2

Chapter 2 discusses building envelopes in Northern Canada and proposes a fundamental conceptual design framework to develop adaptive envelopes for Northern climates which could respond to biophilic, photobiological, and thermal needs of occupants. The importance of building envelopes and adaptive envelope systems to address photobiological and biophilic needs of occupants under extreme climatic conditions of Northern Canada are explained. Main characteristics and features of adaptive envelope systems are explored based on previous studies and different practices for various building uses and climates. Major performance indicators to evaluate building envelopes are presented in terms of biophilic, photobiological lighting, thermal and energy efficiency factors. The performance indicators are used to discuss the shortcomings of existing Northern building envelopes which are constructed based on the Energy Code of Canada for Buildings. Annex A2 specifically shows the biophilic, photobiological, and thermal/energy performance of existing Northern building envelopes which are most often built with a single skin with a low window-to-wall ratio (WWR), i.e., around 20%. A model of Northern building envelopes with an average WWR, around 40%, was also evaluated to enable discussing the impacts of openings. Details of experimental and numerical methods for biophilic, healthy lighting, thermal and energy evaluations are summarized in Annex A2 and further explained in chapters 3 and 4. As presented in Annex A2, photobiological lighting performance of envelope models was evaluated through developing an experimental set-up with prototypes at the scale of 1:50. The experimental set-up was used to capture daylighting under clear skies inside a 1:50-prototype of an open-plan office in Northern Canada, as a case study. The numerical models of the conventional envelope models were also developed to evaluate the annual spatial daylighting performance inside the reference open-plan office in Northern Canada. The biophilic, thermal and energy performance of the envelope models were also evaluated through numerical methods which were developed for the reference office under Northern Canada's climatic conditions, as offered in Annex A2. The results of evaluations in Annex 2 provide a strategic insight to the deficiencies of existing Northern building envelopes' configurations. The results also highlight essential requirements to respond to biophilic and photobiological needs of Northern occupants combined with energy efficiency factors.

Chapter 2 draws attention to the potentials and deficiencies of existing adaptive envelope models to fulfil occupants' wellbeing needs and energy efficiency requirements in Northern climates. Approximately 30 models of adaptive envelope systems, which are constructed in different climates for various building uses, were reviewed in terms of biophilic, photobiological lighting, thermal and energy factors. The review was synthesized in relation to occupants' needs, especially photobiological requirements, under Northern climatic conditions. Reviewing several adaptive envelope systems enabled identifying main architectural configurations and design variables which could modify buildings' biophilic and photobiological performance. The basic architectural structure of adaptive envelopes consists of multiple skins applied to the building facades with different in-between depths. Annex A2 evaluated potential impacts of the basic architectural structure of adaptive envelopes on the performance indicators of the reference open-plan office in Northern Canada. Three models of multi-skin envelopes with different intermediate depths, from a small cavity to transient and habitable spaces, were evaluated in terms of biophilic, photobiological lighting, thermal/energy factors. A high WWR ratio, around 80%, was considered for the interior skin of the multi-skin envelope models which could hypothetically offer higher biophilic and daylighting performance. The overall performance of the multi-skin envelopes models with high WWRs was compared to the Northern buildings' single-skin envelopes with low and average WWRs, i.e., between 20% to 40%. Annex A2 concludes the potentials and shortcomings of the proposed multi-skin envelopes to respond to occupants' needs and Northern climatic conditions compared to the existing Northern buildings' single-skin envelopes.

The discussions of Chapter 2 and evaluations of Annex A2 were synthesized to propose an integrative design framework for effective applications of adaptive envelope systems in Northern Canada. The synthesized framework includes the configurations, openings, and shading elements of adaptive envelope systems with multiple skins which could affect biophilic, photobiological lighting, thermal and energy performance of buildings under Northern climate conditions. The fundamental integrative design framework could enable developing and optimizing adaptive envelope configurations and adaptation mechanisms for occupants' photobiological-psychological needs and energy issues in

Northern climates. The overall design framework consists of three phases of processing environmental data, processing adaptation scenarios, and operating adaptation scenarios. Each phase is explained in detail. Different adaptation behaviours of adaptive envelopes are explained in relation to the identified phases. Main environmental data required for evaluations of indoor-outdoor environments and occupants' needs are determined. Developing a sensory environment to capture main environmental parameters and occupant behavior towards the envelope system is discussed in phase 1. Integrated lighting and thermal adaptation scenarios are explained in phase 2 with regards to the main criteria and parameters for lighting adaptation scenarios, as proposed in Annex A1. Phase 3 offers a methodology for parametric studies of adaptive envelope configurations in terms of main design variables affecting biophilia, photobiological lighting, thermal and energy indicators. The conclusions of chapter 2 and annex A2 combined with the outlines of chapter 1 and annex A1 call, particularly, for developments of shading panel (SP) systems in terms of photobiological lighting parameters and lighting/thermal adaptation scenarios. SPs could potentially play a key role in optimizing biophilic, photobiological lighting, thermal and energy performance of adaptive envelope systems under Northern climatic conditions. Photobiological impacts of SPs have not, yet, been studied.

Perspective on Chapter 3

Chapter 3 aims at exploring human-centric (photobiological) lighting performance of SPs and identifying the impacts of different SPs' design variables on healthy parameters of daylighting for potential applications under Northern daylighting and seasonal photoperiods. Chapter 3 also aims at developing an experimental visualization methodology to capture and evaluate photobiological lighting parameters in architectural models which are most often used during early stages of the architectural design process. The human-centric lighting approach identifies photopic and melanopic units combined with color temperatures of lighting as photobiological parameters representing potential IF and NIF responses of building occupants. Photopic units of lighting represent potential IF effects. Melanopic units and color temperatures of lighting correspond to NIF effects. Chapter 3 provides a theoretical framework explaining the relationships of photopic and melanopic units, ratio of melanopic/photopic (M/P) and correlated color temperature (CCT) for different lighting conditions. The main hypothesis in Chapter 3 is that the color, reflectance, orientation, and openness of SPs could modify the intensity and distribution of daylighting photopic and melanopic units and color temperature in the building. Previous research has not studied impacts of such SPs' variables on photobiological lighting parameters related to NIF effects. Studies have been focused on SPs' impacts on parameters related to IF effects such as visual comfort, glare, and illuminance at the horizontal working plan. Several examples of existing SPs are presented which show applications of shadings in different colors and reflectance. Examples of SPs show that no particular attention has been given to potential NIF responses of occupants for different activities in the building. The human-centric lighting performance of SPs' variables was evaluated through developing an experimental set-up with 1:50 lab scale physical models. The experimental set-up enables HDR imagery inside the model and post-processing per-pixel lighting analysis under clear skies. Approximately 40 models of 1:50 scale SPs were produced by considering different colors, as blue, red, white, and wood, reflectance, as glossy and matt finish, orientations, as horizontal and vertical, and openness, from large to small. SPs' colors were chosen to potentially affect different spectrums of daylighting. HDR imagery was developed to capture light inside the scale model from back and side views by using Raspberry Pi camera modules mounted with fisheye lenses. The process to generate and calibrate HDR images are explained in detail. HDR images were post-processed to render false color maps and violin plots of photopic and melanopic units, M/P ratios, and color temperatures. The results are discussed in terms of different SPs' variables' impacts on photobiological lighting parameters. Potential adjustments of different SPs' variables to photobiological lighting adaptation scenarios in Northern Canada are, also, discussed. The conclusions of Chapter 3 clarify the relationships of SPs' variables, especially the color scheme and reflectance, and photobiological daylighting parameters in the space. Chapter 3, also, concludes main issues that must be considered in future developments of SPs for efficient applications under Northern climatic conditions. The developed experimental methodology with physical models is also shown that could improve understanding of lighting conditions in relation to architectural variables during the design process of buildings.

Perspective on Chapter 4

Chapter 4 aims at developing a fundamental model of adaptive high-performance envelopes based on biophilic and photobiological indicators for Northern buildings which could provide efficient indoor-outdoor connections and foster positive occupants-nature relationships. The fundamental model of adaptive envelopes is developed in terms of biophilic, photobiological and thermal indicators which represent occupants' wellbeing and energy requirements under extreme Northern climatic conditions. The proposed model of adaptive high-performance envelopes consists of essential elements and configurations which could optimize biophilic, photobiological lighting, and thermal indicators. The efficiency of proposed elements and configurations is studied through experimental and numerical methods. Numerical models were used to evaluate and optimize biophilic performance of the proposed adaptive envelope. Biophilic performance indicators are formulated in terms of direct/indirect, visual/non-visual, controllable/non-controllable and sequential/non-sequential connections with the outdoor natural phenomena and naturalistic features. The results are, particularly, shown that the proposed envelope system optimizes individuals' direct visual connections with the outdoor sub-Arctic natural phenomena, daylighting availability and seasonal photoperiods.

Experimental methods using 1:10 scale physical models, HDR imagery and post-processing techniques were employed to evaluate impacts of proposed envelope configurations on photobiological lighting parameters. Experiments were conducted under actual clear skies with direct sun lighting and artificial overcast skies with diffuse lighting in different color temperatures which were identical to Northern daylighting conditions. The experimental set-up enabled comprehensively studying the shading system of the proposed envelope configuration in terms of different design variables. Approximately 23 prototypes of colored SPs with matt/glossy reflectance were evaluated under different horizontal/vertical orientations, upwards/downwards and left/right inclinations, low to high densities, small to large sizes, and top/bottom positions at windows. SPs' colors are chosen to affect different portions of daylighting spectrums. The results of healthy lighting evaluations are synthesized to adapt the shading system of the proposed envelope to lighting adaptation scenarios which are developed in chapter 2 and Annex A2. The developed shading system and adaptation scenarios are further improved by considering panels to be made of insulation materials.

A simplified numerical model is used to evaluate the thermal and energy performance of the proposed adaptive envelope configuration with scheduled insulated panels for the reference office in Northern Canada. The results of thermal models reveal the higher thermal and energy efficiency performance of the proposed envelope configurations compared to conventional Northern building façades. The thermal evaluations, also, reveal that the intermediate space of the proposed envelope could offer warmer temperature compared to the exterior outdoor weather during the cold winter months.

The conclusions of chapter 4 recommend applying the proposed adaptive high-performance envelope systems for different Northern buildings. The research results suggest that applying biophilic adaptive high-performance envelope systems could foster efficient positive relationships with the outdoor sub-Arctic nature through improving building performance and responding to occupants' wellbeing needs. Chapter 4, also, outlines major issues for future development of biophilic photobiological Northern buildings with adaptive high-performance envelope systems.

Perspective on the thesis Conclusions

The final chapter of the dissertation concludes the key contributions of the research and outlines for future developments. The dissertation conclusions draw attention to the theoretical and architectural frameworks and strategies as well as methodological approaches which have been developed to address occupants' photobiological-psychological wellbeing, biophilic adaptive building envelopes, and climatic conditions in Northern Canada. The outcomes of the research could effectively inform architects, lighting designers and decision-makers about biophilic photobiological developments of buildings and envelopes in Northern climates. The dissertation conclusions also outline several issues for future developments, especially in terms of a (i) comprehensive biophilic design approach to healthy buildings in Northern climates, (ii) life cycle, economic efficiency and durability, resilience and robustness of adaptive envelopes' materials and mechanism in extreme sub-Arctic climate, (iii) integrative performance evaluations with emphasize on photobiological lighting and indoor environmental quality, (iv) photobiological lighting evaluations of shading systems in relation to surface characteristics of indoors and intermediate spaces and artificial lighting, and (v) sociocultural and subjective aspects of biophilic design, adaptive envelope systems and photobiological buildings.

Chapitre 1: A photobiological approach to biophilic design in extreme climates

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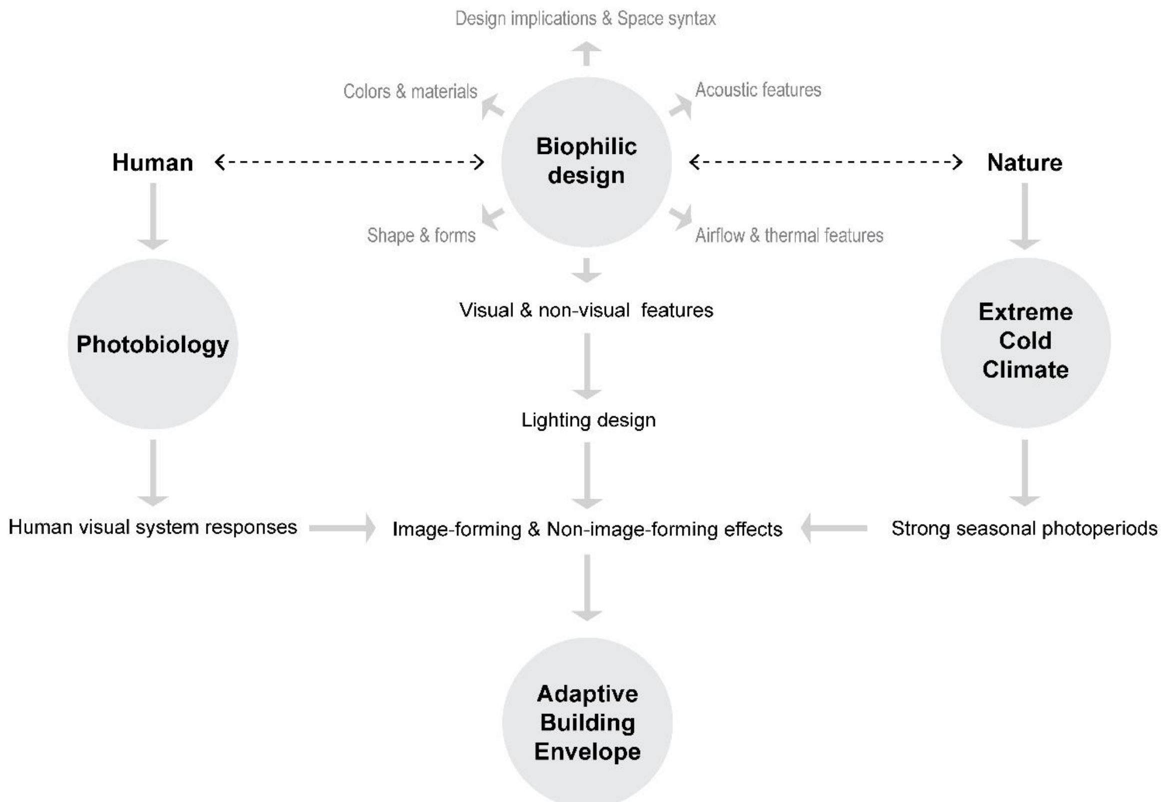
Highlights

- The biophilic design approach has potential benefits in extreme cold climates, especially for Nordic occupants.
- Lighting design should be developed to deal with the challenging state of living and working in northern latitudes.
- Non-image-forming effects of light have become the missing link between human needs and lighting design standards.
- Adaptive envelopes should be developed to optimize biophilic quality and fulfil the photobiological needs of Nordic people.

Graphical Abstract



1.1 Résumé

Cet article propose l'approche de la conception biophile comme une hypothèse plausible pour répondre aux conditions difficiles de vie et de travail dans des climats extrêmement froids. La conception biophile a récemment été développée pour remédier aux effets négatifs de l'environnement bâti et pour améliorer le bien-être de l'homme à travers une redéfinition de la relation homme-nature. Cependant, la conception biophile devrait être adaptée aux climats froids extrêmes afin de répondre aux besoins biologiques des occupants des territoires du nord. Cette question prend toute son importance dans un contexte de disponibilité de lumière naturelle fortement affectée par les changements de photopériode saisonnière et des conséquences sur le bien-être humain dans ces régions. Le présent article examine de manière critique les caractéristiques de conception biophile pour en déterminer les limites principales. Les limites incluent l'absence (1) de recommandations applicables aux climats froids extrêmes, (2) d'adaptation aux photopériodes locales, et (3) d'un cadre systémique intégrant le processus de conception. L'article attire l'attention sur les effets de formation d'images et de non-formation d'images de la lumière comme base de l'approche de conception homme-nature. À cet égard, les résultats photobiologiques ont été étudiés. Ensuite, l'article discute des normes et recommandations existantes en matière d'éclairage en Amérique du Nord et comment elles ont été principalement développées pour répondre aux demandes de formation d'images de la lumière. Plus d'efforts sont nécessaires pour réviser ces normes en ce qui concerne les effets non formateurs d'images de la lumière et les exigences de design biophilique. Enfin, les enveloppes adaptatives des bâtiments sont présentées comme une solution hypothétique pour optimiser les qualités biophiles des bâtiments et répondre aux besoins biologiques des personnes vivant et travaillant dans des climats froids extrêmes dans les territoires du nord.

1.2 Abstract

This paper proposes the biophilic design approach as a plausible hypothesis for the challenging conditions related to living and working in extreme cold climates. Biophilic design has recently been developed to overcome the adverse effects of the built environment and to improve human well-being by redefining the human-nature relationship. Yet, biophilic design should be adapted to extreme cold climates in order to meet the biological needs of people in northern territories. This issue becomes more important when considering the availability of natural light due to the strong seasonal photoperiod and its effects on human well-being in such regions. The present paper critically reviews biophilic design patterns and identifies their main shortcomings. These shortcomings include the lack of (1) recommendations applicable to extreme cold climates (2) adaptation to the local photoperiods, and (3) a systemic framework integrated into the design process. The paper draws attention to the image-forming and non-image-forming effects of light as a basis of the human-nature design approach. In this regard, photobiological outcomes have been reviewed. Then, the paper discusses the existing lighting standards and guidelines in North America and how they have mainly been developed to fulfil the image-forming demands for light. Further efforts are needed to revise these standards with respect to the non-image-forming effects of light and the biophilic design requirements. Finally, adaptive building envelopes are presented as a hypothetical solution to optimize the biophilic qualities of buildings and address the biological needs of people living and working in extreme cold climates in northern territories.

1.3 Introduction

The biophilic design approach has potential benefits in extreme cold climates, especially for Nordic occupants. Biophilic design is among recent approaches to improve the interactions and positive relationships between human beings and nature in the built environment. The idea of biophilic design originated in the theory of biophilia. Etymologically, the word ‘biophilia’ comes from the Greek word meaning “love of life” [15]. The theory of biophilia was first propounded by Wilson [5]. This theory rests on people’s inherent affinity towards life and lifelike processes and patterns. The development of the biophilia hypothesis is based on biological science and human needs. From a biological standpoint, humans are a part of nature and they synchronize to the environmental conditions [16, 17]. The theory of biophilia shares this view. It considers humans like other species who have steadily evolved to adapt to nature [2, 3]. The theory of biophilia emphasizes the psychological, emotional and spiritual dimensions of human well-being that result from innate human-nature relationships [18, 19]. These relationships exist throughout the world thereby suggesting that they go beyond any cultural and ethical differences [20]. In the field of the built environment, the nature-orientated design of architectural and urban spaces has thus been accentuated in the biophilic approach. Yet, no studies have been conducted to assess the use and adaptation of the biophilic approach to human needs in extreme climatic conditions.

The biophilic design approach intends to reconnect and promote the human-nature relationship and eventually express this innate relationship in human lives [19, 21]. Biophilic design claims that this relationship with nature is vital for human beings [21, 22]. It argues that architecture is capable of expressing individuals’ physiological and psychological inclination to nature [19]. This architectural approach can ultimately create forms and spaces to inhabit that answer the design problem defined by different contexts [23, 24]. In this regard, biophilic design is an intelligible language of architectural spaces that is instinctive to human demands by presuming natural forms and patterns as vocabularies and compositional grammar [15]. A perfect biophilic design integrates nature into the built environment in a way that is restorative and inspirational without causing any disturbance to the function of the space [25]. Hence, designers can imagine buildings that are delightful, functionally productive and regenerative through a clear understanding of lifelike patterns and their interactions with human needs [26]. However, the use of the proposed biophilic design guidelines during the design process comes with many difficulties and obstacles.

The present paper discusses the body of knowledge in biophilic design and identifies its shortcomings for applications in extreme cold climates. Firstly, the paper discusses the difficulties and limitations of the suggested biophilic patterns in extreme environments by comparing a selection of climates. Secondly, shortcomings of lighting design are discussed in relation to the potential of photobiological science to build human- and nature-friendly spaces. Thirdly, the structural weakness of biophilic design to accomplish its mission is discussed. Finally, a hypothetical solution to overcome the identified gaps and shortcomings is proposed. Moreover, the study is conducted based on a critical review of knowledge in biophilic design, photobiology, and lighting design. In this regard, recent research, publications, standards, and guidelines (in North America) related to biophilic design, biological effects of light and lighting design were considered. Several databases were searched including Web of Science, ScienceDirect, and SCImago. The publications were organized according to specific keywords related to photobiology, biophilic design and lighting design. Such keywords include biophilic design, biophilia, nature-friendly design, human needs, design process, image-forming and non-image forming effects, lighting design, lighting analysis, and metrics. Several review papers related to the keywords were also reviewed. The number of studies selected for review accounts for about 85 documents on biophilia, 120 documents on image-forming and non-image-forming effects, and 80 documents on lighting design. As explained in the following sections, several climate classifications were also reviewed to discuss climate conditions.

1.4 Biophilic design constraints in extreme climates

Biophilic design guidelines should be adapted to extreme cold climate conditions. Natural environments change annually from winter to summer conditions, as illustrated in Figure 1.1. This situation typically intensifies from a temperate climate (Figure 1.1, middle) to an extreme hot or extreme cold climate when moving to lower latitudes (towards the equator, Figure 1.1, right) or higher latitudes (towards the Arctic, Figure 1.1, left), respectively. However, the current biophilic design strategies were mainly developed for temperate climates. Climate classifications enable to clearly identify the importance and deficiencies of biophilic design patterns in extreme cold climates. Overall, four basic categories of climate classifications have been developed including (1) generic (2) genetic (3) climatic comfort (bioclimatic) and (4) energy and moisture budget classifications [27, 28]. In response to different latitudes and building applications, several guidelines have been devised based on such climate classifications. In terms of human comfort, bioclimatic classification schemes have been developed to analyze the weather and climatic conditions. These bioclimatic classifications mainly consider the physiological and psychological reactions of people to climatic parameters [28, 29]. One well-known classification is the ASHRAE climate zone. ASHRAE [30] provides a global climate zone classification system for the energy demand analyses in the built environment. It includes seventeen climate zones regrouped in eight main categories. The ASHRAE climate zone classification is based on four environmental factors namely heating degree days (HDD), cooling degree days (CDD), monthly mean temperature and monthly precipitation.

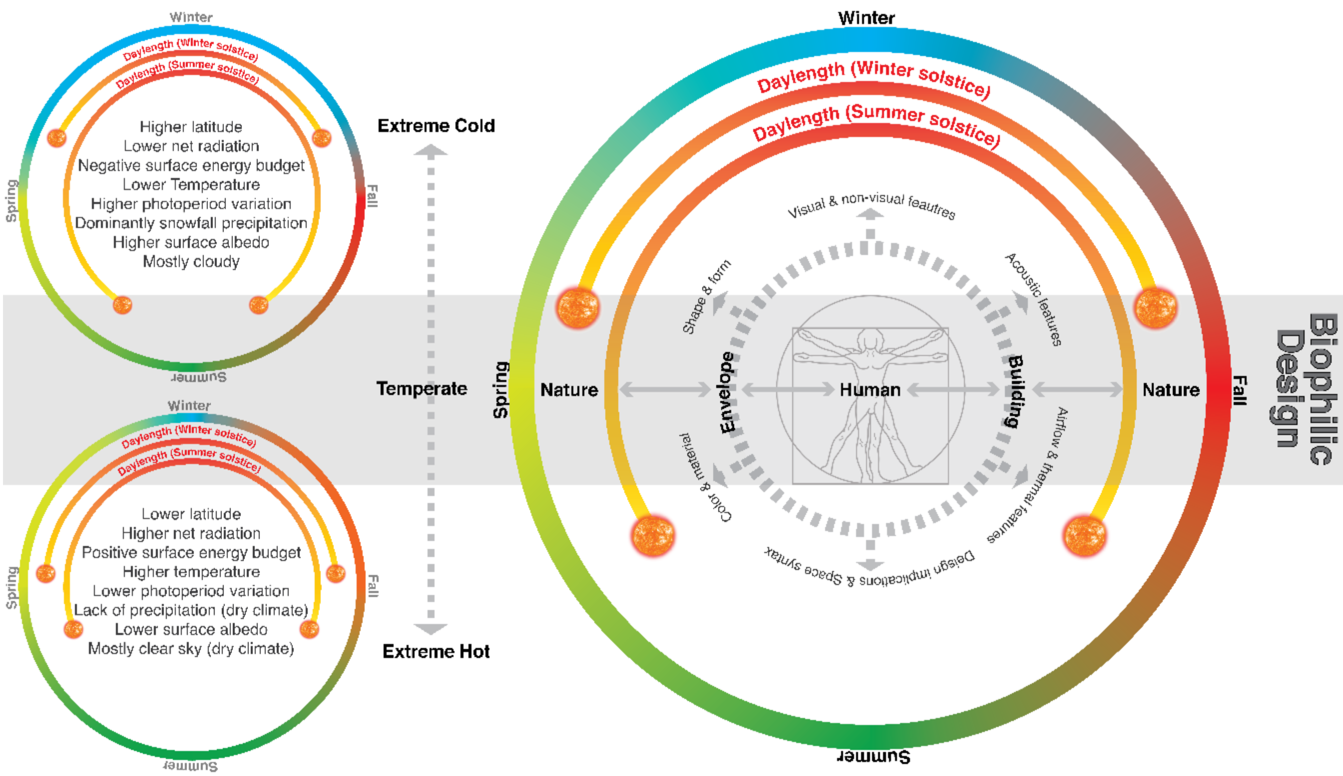


Figure 1. 1. The built environment features emphasized by biophilic design strategies in relation to dynamic climatic conditions

Solar radiation and the photoperiod are identified as the main climate-causing factors [31] that trigger several biological and socio-cultural events [13, 32]. They influence inhabitants and man-made settlements economically, socio-culturally, and physio-psychologically. However, climate classifications have mainly been focused on thermal aspects of solar radiation, neglecting the biological effects of seasonal photoperiods. In this regard, Figure 1.2 shows the global illuminance patterns related to the sun. Considering the basic curve of a clear sky (shown in red in Figure 1.2), the global illuminance increases logarithmically from about 450 lux during sunrise/sunset to around 110,000 lux when the sun reaches its zenith at a position located 90° above the horizon. It should be noted that daylight illuminance depends on geographical locations and that the sun reaches the zenith at a smaller angle for regions near the equator (between +/-23°). Figure 1.3 presents an overview of lighting features for three cities located in different climate zones and latitudes. Meanwhile, Figure 1.4 shows an overview of thermal features in these cities. As can be seen, the photoperiod, shadow pattern, sun path, temperature, cloud cover, humidity comfort level and solar radiation significantly change from Los Angeles (Lat. 33,9°N) to Montreal (45,5°N) and Kuujjuaq (58,1°N). More specifically, in the extreme cold climate of Kuujjuaq (Figure 1.3, right column), people experience longer days without complete darkness during the summer, a situation approaching 18 hours of daylight, from 3:30a.m. to 9:40p.m. in June. On the contrary, people are exposed to only a few hours of daylight during the winter: about 6.5 hours of daylight from 8:30a.m. to 2:30p.m. in December. In comparison, the day/night cycle is extended moderately in the temperate Los Angeles climate, from around 10 hours (around 7a.m. to 5p.m.) of daylight in December to nearly 14.5 hours (around 5a.m. to 8p.m.) of daylight in June (Figure 1.3, left column). Thus, the solar radiation and the photoperiod are more challenging in the northern latitudes. In brief, dramatic seasonal photoperiod variations result in a lack of solar radiation and of light in the winter months combined with a few hours of darkness in the summer months. Overall, the climate features of northern territories include: (1) strong seasonal photoperiod variations; (2) low net radiation; (3) high surface albedo; and (4) mostly cloudy skies throughout the year, with snowfall precipitation in the winter. This situation results in a negative surface energy budget, very low seasonal average surface and air temperatures and ultimately, severe environmental conditions [31, 33].

An extreme cold climate creates difficult conditions for living and working in the North. While the Inuit people (here called inhabitants [34]) adapt well to this extreme climate, non-adapted populations (here called occupants [34]) face many difficulties. Nordic occupants are forced to spend more than 90% of their time indoors with limited connections to the natural environment [35, 36]. Meanwhile, the vernacular and Inuit architecture is well adapted to such harsh natural conditions (for example see [37, 38]). However, the recently built modern settlements and buildings have most often been designed with little consideration for the harsh natural elements and the strong seasonal photoperiod. These buildings are mainly designed with a high thermal resistance envelope to satisfy the thermal comfort and indoor air quality demands [39, 40]. In the north of Quebec, the models imported from the south are not designed to provide northern occupants with desirable light and darkness throughout the year. This situation generates adverse effects on human well-being, both physiologically and psychologically. In this regard, previous studies reported several light-related complaints of sub-Arctic occupants such as desynchronized circadian clocks, sleep problems, lower physical activity, seasonal affective disorder (SAD), mood disturbances and higher UV light exposure [41-43]. Furthermore, the energy consumption of buildings increases because occupants are more disconnected from the exterior climatic conditions and cycles, and thus rely heavily on the interior environment to compensate. Therefore, there are higher demands for artificial lighting and mechanical heating systems which lead to negative environmental impact. Overall, this problematic situation exerts greater pressure on the economy due to excessive demands for energy production, the control of environmental risks and the additional pressure on the health-care system. The next section discusses lighting design strategies regarding these issues.

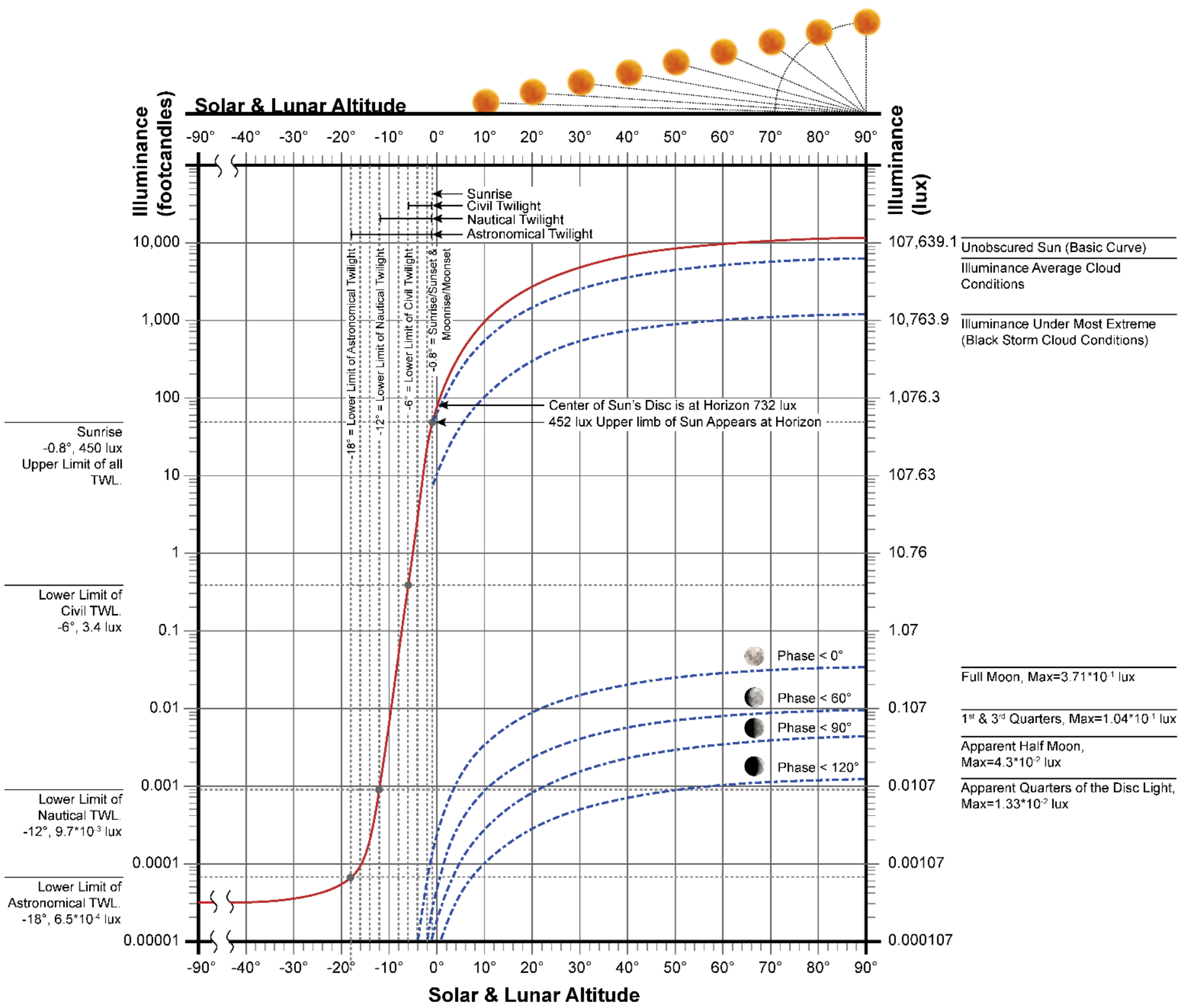


Figure 1. 2. Global illuminance patterns versus solar and lunar altitude (Retrieved from Thorington [44])

Considering the challenges faced in northern climates, biophilic design has potential advantages. More specifically, the well-known guideline suggested by Kellert [2] consists in two basic dimensions of biophilic design. These dimensions are related to six design elements and over seventy design attributes. An updated version of this guideline includes three major experiences, namely: (1) direct experience of nature; (2) indirect experience of nature; and (3) experience of space and place [3]. This guideline also proposes twenty-four attributes of biophilic design. Another guideline, proposed by Heerwagen & Gregory [45], mentions seven attributes of nature-inspired biophilic design. These attributes include sensory richness, motion, serendipity, variations on a theme, resilience, sense of freeness and prospect and refuge [45]. Moreover, Browning et al. [1] identified fourteen patterns of biophilic designs, which they regrouped in three categories, namely: (1) nature in the space; (2) natural analogous; and (3) nature of the space. Overall, the proposed biophilic design strategies emphasize the nature-oriented design of specific features of the built environment, as depicted in Figure 1. 4. Such features include (1) visual and non-visual features; (2) airflow and thermal features; (3) acoustic features; (4) colors and materials; (5) shape and form; and (6) design implications and space syntax. It is claimed that biophilic design patterns are flexible and replicable in various climatic or cultural situations [1]. Yet, the usability, adjustability, and productivity of biophilic design guidelines for such climates have not been assessed.

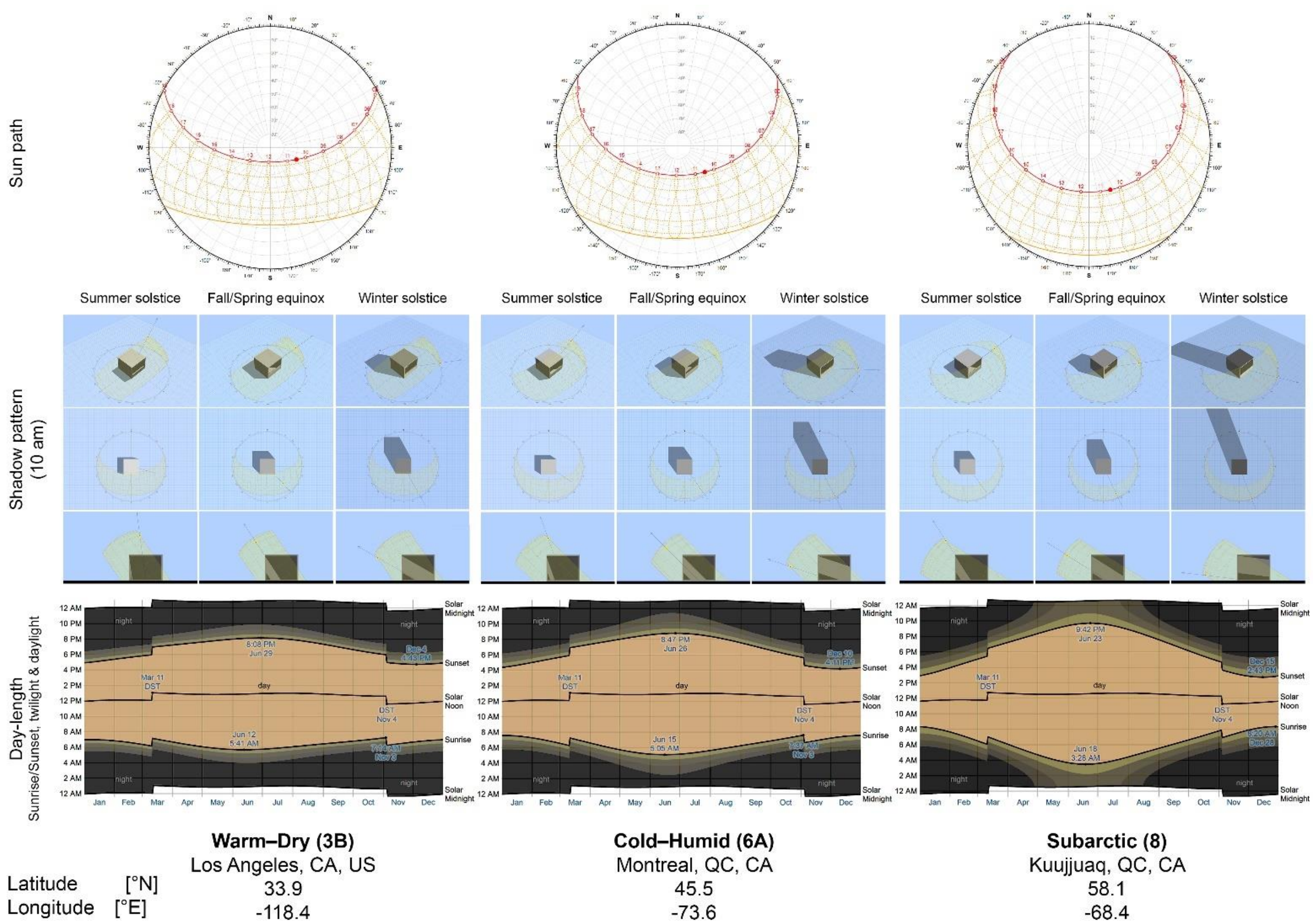


Figure 1. 3. Lighting features of three North American cities located in different climates (meteorological data is derived from TMY-2 published by EnergyPlus and figures are derived by using Weather spark [46] and online tools offered by Marsh [47])[1]

[1] *This figure is revised to use in the thesis based on the jury's comments.*

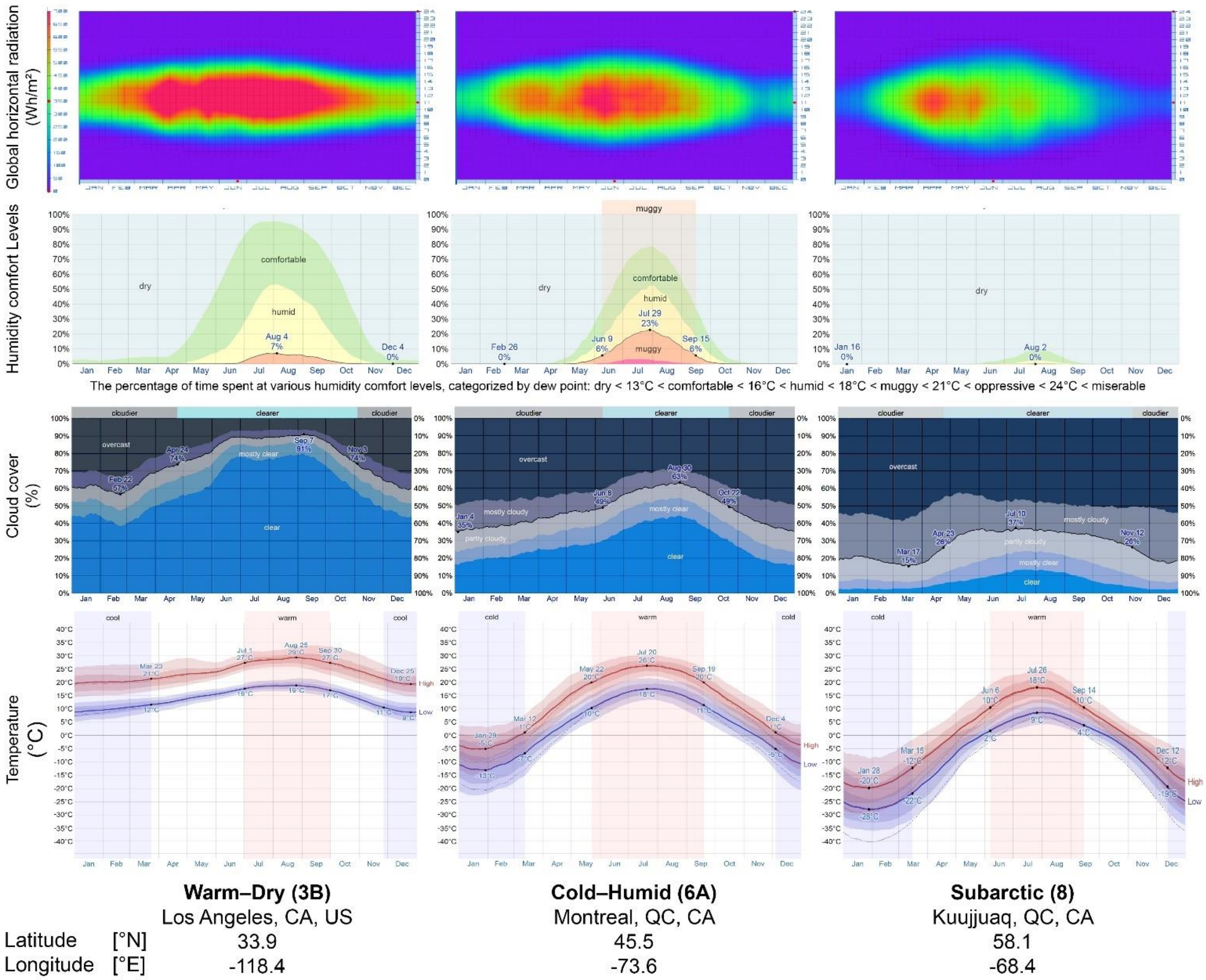


Figure 1. 4. Thermal features of three North American cities located in different climates (meteorological data is derived from TMY-2 published by EnergyPlus and figures are derived by using Weather spark [46] and online tools offered by Marsh [47])

Biophilic design recommendations should be developed and adapted to the harsh nature of the north. More specifically, biophilic design guidelines mainly highlight the environmental aspects of buildings, such as interactions with plants, water, natural materials, views to natural landscapes, natural shapes and geometrical features of biological forms like fractals, scale invariance, natural light and light with qualities found in nature, fresh air, etc. [15]. Such biophilic patterns have potential benefits for extreme climates. However, the main questions related to the application of biophilia in extreme climates need to be addressed: How can a designer develop biophilic design recommendations for a severely cold or hot climate? How is it possible to take advantage of such extreme natural conditions in building design? Taking advantage of the biophilic design approach therefore calls for practical and appropriate strategies for the extreme climates of Nordic regions.

1.5 Major deficiencies of lighting design

Lighting design is one of the major elements to develop within biophilic design in order to deal with the challenging conditions related to living and working in extreme cold climates. People are exposed to the light provided by the design and control strategies of the built environment, which consequently affects their health. Hence, lighting design plays a key role in human-nature relationships and the theory of biophilia [1, 2]. Biophilic design patterns aim at maximizing the use of sunlight and skylight, directly and indirectly, and modifying the design of artificial lighting to be sufficiently nature-friendly [1, 3]. Meanwhile, visual and non-visual responses to nature and natural systems are other concerns of the biophilic approach that should be considered in lighting design [1, 3].

Growing attention has recently been given to the design of lighting in buildings to make them more restorative and adapted to nature-human relationships [25, 48]. The science of photobiology has thus far acknowledged the image-forming (IF) and non-image-forming (NIF) effects of environmental light on human beings. Photobiology is the science that studies the responses of humans, animals and plants to the local and systemic effects of optical radiation in the range of UV, visual (human visual system sensitive) and IR [49]. An IF visual response refers to the complex biological process that enables vision or image formation in human beings when light reaches the eyes [13, 50]. Incident light also stimulates several brain areas implicated in circadian rhythm regulation, alertness, well-being and moods; these are the body's NIF visual responses to light [13, 50]. In the built environment, inhabitants' photobiological responses are potentially affected by lighting systems and the opportunity of receiving daylighting. Yet, research on the built environment has mostly focused on the energy and visual comfort aspects of lighting systems. Therefore, other interactions of humans with light, in particular NIF effects, have been neglected. Moreover, the challenging light/dark cycle of northern regions has escaped the attention of researchers and designers. Generally, three major fields of lighting study in the built environment can be identified namely:

- **Energy aspect:** Over the past few decades, a considerable amount of research has been carried out to assess the energy aspects of lighting systems in terms of heat transfer and energy efficiency for example Yu and Su [51].
- **Sociocultural aspect:** A few studies discuss the socio-cultural aspects of light in the built environment. Humans organize the built environment according to four elements: "space,"

"time," "meaning" and "communication" [52]. People make their living spaces meaningful by transforming the spaces and its components into some recognizable signs or adding signs [53]. Considering architecture as a system of signs [53, 54], socio-cultural studies explore the meanings, interpretations and ultimately communicational effects of light, as one element of space, in the built environment [54]. This area of light studies is still ongoing.

- **Human well-being aspect:** Light affects human beings through IF and NIF processing. However, the NIF effects of light on building occupants have escaped the attention of built environment researchers in comparison to the number of studies on its visual effects. More specifically, numerous studies have been conducted in the past few years to explore the interaction of light/daylight and the built environment with respect to visual comfort, analysis factors/metrics, analysis methods, simulations and measurements, impacts of windows and openings, shading and control strategies, and effects of materials [13, 50, 55, 56].

In North America, lighting design standards and recommendations have mostly been developed to address human visual comfort, energy efficiency and electrical safety issues [57, 58]. The NIF effects of light, which produce undeniable effects on human well-being [59, 60], have been neglected in lighting design standards. Furthermore, existing standards do not necessarily relate to the objectives of biophilic design. Thus, further research and development is necessary to establish guidelines in terms of NIF effects [57] and the biophilic quality of light in the built environment. The climatic conditions, particularly in Nordic regions, should also be addressed.

1.6 Contribution of photobiology to lighting design

Photobiological science should be integrated to lighting design standards to eventually produce comprehensive and appropriate guidelines for human needs in North America. To this end, employing the photobiological outcomes represents a recent effort to link lighting design with human health [61]. Fundamentally, optical radiation refers to a physical quantity transporting energy through radiation or literally electromagnetic waves [13, 62]. Optical radiation includes a series of spectra with different wavelengths, photon energy and power between the region of transition to X-rays ($\lambda \approx 1$ nm) and the region of transition to radio waves ($\lambda \approx 1$ mm). Meanwhile, the term 'light' refers to different concepts, as suggested by the '*Commission internationale de l'éclairage (CIE)*' [63]. In some cases, it is used to describe the characteristic of all sensations and perceptions through vision. The term 'perceived light' is also used for such purposes. In other cases, it is used to represent radiation, which can stimulate the human visual system [63]. As depicted by Figure 1.5, every bandwidth has a specific name, effect and energy. The bandwidth of approximately 360 to 830 nm corresponds to visual light (Figure 1.5). To produce photobiological responses, the incident optical radiation must first be selectively absorbed by molecules of a living organism. Consequently, two types of reactions, namely photophysical and photochemical reactions, trigger a biological response [13].

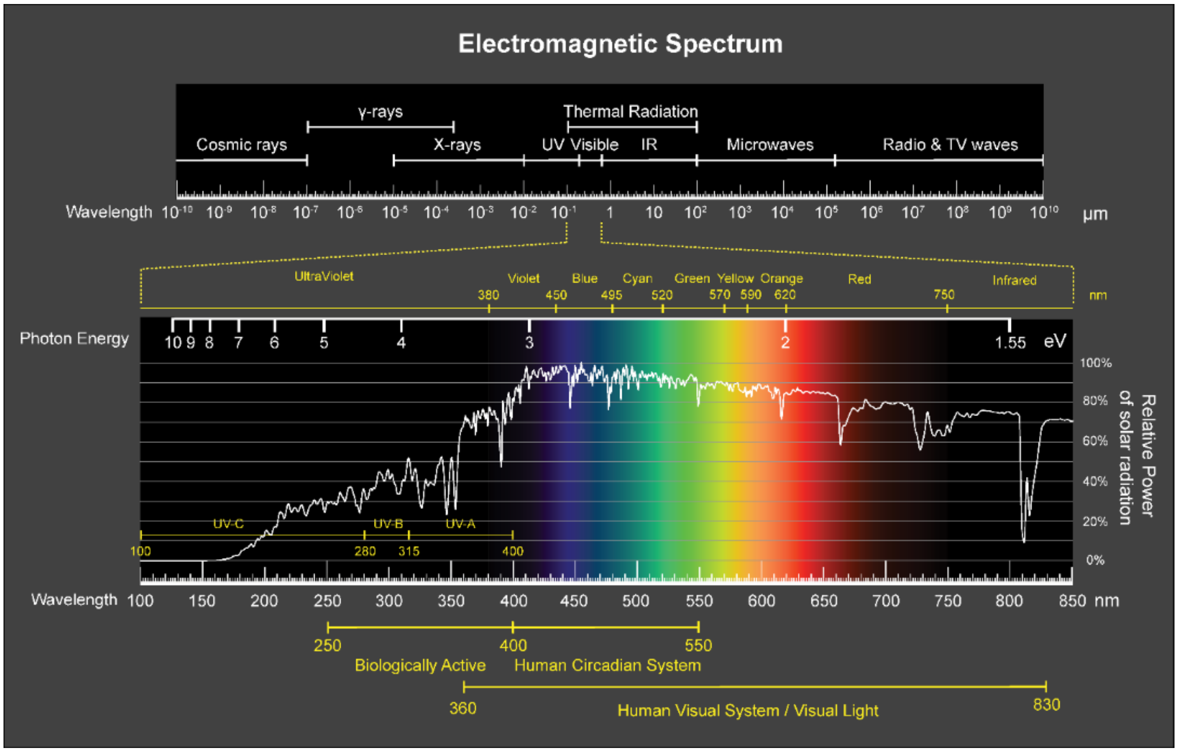


Figure 1. 5. Electromagnetic spectrum and corresponding photon energy and relative power at each wavelength from 100 to 850 nm and the approximate color associated with those wavelengths. The graphs are based on the data given by DiLaura, et al. [13], Baron and Suggs [49], Boyce and Raynham [58], ASTM G173-03 [64]

1.6.1 IF effects in built environments

In the built environment, inhabitants' IF perception of light is acutely affected by lighting systems and spatial components. Light can be provided through different means in buildings. Several photometric functions have been developed to describe and evaluate the various light impulse parameters that influence human vision. These functions are extensively employed in lighting design. Table 1.1 provides a summary of the visual responses to different light parameters such as quantity, spectrum, and duration along with corresponding photometric metrics, units, and equipment. Three broadly discussed light functions are the photopic and scotopic luminous efficiency and the relative spectral sensitivity. Accordingly, the photopic and scotopic luminous efficiency points to the action spectrum of vision for photopic and scotopic adaptations [13]. As shown in Figure 1.6-A, V(λ) and

V'(λ) represent the relative spectral sensitivity functions of photopic and scotopic luminous efficiency normalized at 555 and 505 nm for a standard observer with 2º and 20º visual fields, respectively [65-67]. Most of the lighting design studies have thus far focused on specific IF effects of light including [13, 62]:

- Luminance ratio and distribution
- Illuminance level, distribution, and uniformity
- Glare
- Directionality of light
- Color rendering and color appearance of the light
- Material impacts on light visual perception
- Flicker
- Daylight metrics

There is a lack of knowledge concerning the interactions of IF effects of light and NIF combined with other biophilic principles such as offering a nature view. Moreover, the severe light/dark cycle of northern territories requires special attention in studies concerning IF effects in the built environment. Therefore, it is arguably necessary to integrate IF with NIF effects in whole building design processes after which, climate-based spatiotemporal analysis methods will be developed for extreme climatic conditions. To this end, recognizing the biological mechanism of the visual system could provide designers with clues about how different parameters of light and space affect the IF and NIF perception of occupants. When light reaches the eyes, it initiates complex chemical and neural interactions between the eye and the brain that result in a visual response-or image formation [13, 50]. This elaborated reaction of the eye-brain system, as one unit, enables humans to observe and ultimately perceive the surrounding world under very low to very high levels of light [13, 50]. The human visual system is sensitive to a specific bandwidth of light, so-called visual light, from 360 to 830 nm [58]. The neural part of the eye is the retina, which is responsible for the absorption of incident light and its transmutation into electrical signals that are convey to the brain visual system by the optic nerve in order to generate image formation [50, 58, 67]. The complex structure of the retina includes three layers, namely the photoreceptors, bipolar cells, and ganglion cells [13, 58, 66, 68]. There are four types of photoreceptors with different photopigments and spectrum peaks that can be categorized into two groups: (1) rods that peak at 491 nm and (2) cones namely L-cones (peak at 560 nm), M-cones (peak at 531 nm) and S-cones (peak at 420 nm) (see Figure 1.6-B) [58, 66, 68, 69]. Cones and rods are basically responsible for day (bright light) and night (very dim light) vision, respectively [70]. Moreover, some specific ganglion cells, so-called intrinsically photosensitive retinal ganglion cells (ipRGC), have recently been identified as photoreceptors. The ipRGC initiate the NIF effects of light, in particular for the circadian system [71]. The next section discusses this issue in more detail.

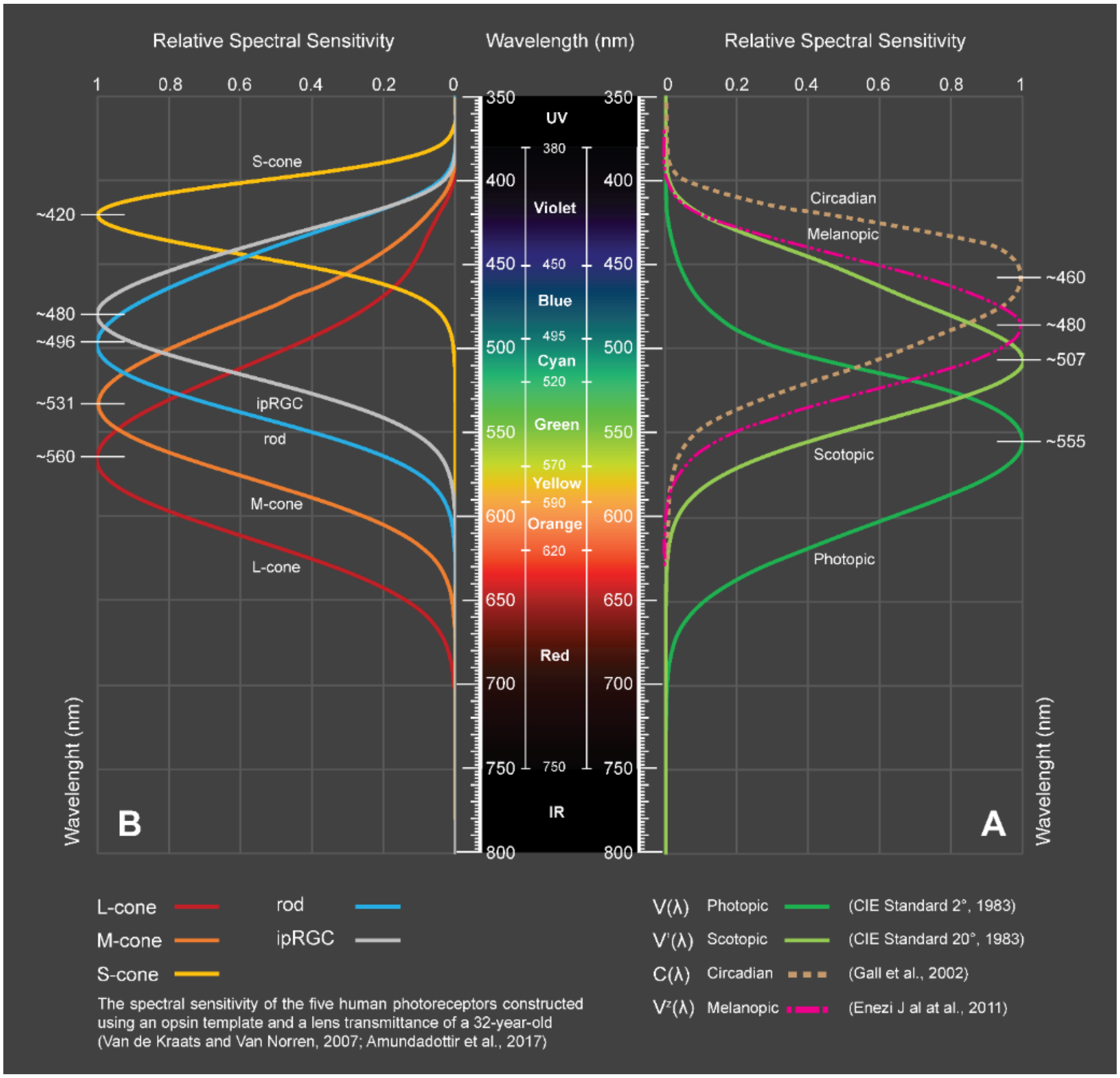


Figure 1. 6. Normalized relative spectral sensitivity for **(A)** the functions of circadian C(λ) [68, 72], melanopic $V^z(\lambda)$ [66, 68], scotopic V'(λ) (CIE 1951), photopic V(λ) (CIE 1924) [13] **(B)**; and the human photoreceptors [68, 73]

Table 1. 1. The IF effects of different parameters of optical radiation on human vision and corresponding photometric units and equipment [13, 50, 58, 74-76]

Light parameter	Impact	Metric	Unit	Equipment
Quantity	● Photopic vision occurs at luminance higher than approximately 10 cd/m2. The visual system in this state of adaptation exhibits a spectral sensitivity to monochromatic optical radiation that is defined by the Standard Photopic Luminous Efficiency Function of Wavelength of the CIE. ● Mesopic vision is intermediate between the photopic and scotopic states occurring at luminance below approximately 3 cd/m2 and above approximately 0.01 cd/m2 ● Scotopic vision occurs at luminance less than approximately 0.01 cd/m2.	Illuminance Luminance	lux Cd/m2	Illuminance meter Luminance meter HDR image
Spectrum	● The canonical visible range is 360–830 nm ● Photopic and scotopic visions peak at nearly 555 and 507 nm wavelengths, respectively. ● UV and IR wavelengths have adverse effects on the vision system.	Wavelength Color temperature Spectral power distribution	nanometer Kelvin $W/m2 \times sr \times nm$ $W/m2 \times nm$	Spectrometer Spectrophotometer Colorimeter Filtered radiometer Spectroradiometer
Timing	● Vision system reacts to inclined light in any time (day/night)	Time	second	–
Duration	● Vision system reacts very short (less than 1 s) to incident light. ● Smooth movements faster than 40° per second or erratic movement at slower speeds will lead to a dramatic deterioration in visual acuity.	Time	second	–
Spatial distribution	● Distribution of light on the eye is important for visual comfort and performance. ● It affects the image formation, ability to distinguish shapes, details and other spatial characteristics.	Measuring the luminous intensity distribution, luminance distribution, luminous flux or spatial color distribution	W W/m2 $W/sr \times m2$	Goniophotometer CCD-based camera systems HDR image with calibrated digital camera
Adaptation	● The human visual system can process information over an enormous range of luminance, from a very dark night (10^{-6} cd/m2) to a sunlit beach (10^{+6} cd/m2) (approximately 12 log units), but not all at once. ● Several important aspects should be noted such as the asymmetry in adaptation speed from low to high (seconds) and high to low (minutes) light levels, and the adaptation to colored scenes and multilevel adaptation mechanisms (Iris, eye lids, retinal adaptation etc.)	Time	second	–
Color	● Color is a human perceptual phenomenon visually experienced and is not an intrinsic characteristic of light spectrum or objects. ● Color perception depends on three components including optical radiation, objects and vision. ● Materials change the reflection, transmission, scattering, and/or fluorescence of optical radiation. ● Human color perception depends on retinal photoreceptors.	Color temperature Correlated Color Temperature (CCT) CIE Chromaticity chart (CIE xyz) Color Rendering Index (CRI)	Kelvin	Colorimeter

One of the highly important concepts in lighting design is color. Color is basically a human perceptual phenomenon that is visually experienced; it is not an intrinsic characteristic of light spectrum or objects. The term color is misleadingly used as a property of objects, since every band of light is denoted as a particular color (as displayed in Figure 1.6) [13, 77]. In fact, color is recognized as the human color vision process of a light source spectral power distribution (SPD) which is modified by an object [13]. In the context of the trichromatic theory of color vision, the human vision system responds to a light SPD through three channels of red/green, yellow/blue, and luminance [13, 58, 77]. These channels are generated by L, M and S cone photoreceptors. Color matching functions (called as CMFs xyz) have been introduced to characterize and standardize the perception of color for research, design, and evaluation purposes. CMFs xyz are used to calculate the tristimulus values for which CIE has published a chromaticity diagram [13, 50, 75].

1.6.2 NIF effects in built environments

Attention to the NIF effects of light in buildings and urban environments has recently increased. Ongoing efforts are being developed to bridge the gap between lighting design and photobiological knowledge of the NIF effects of light. Photobiological studies have revealed several important NIF effects of light on human beings [59, 60]. It is claimed that such effects can cause temporary or even permanent damage that can eventually result in death [78]. The NIF effects are stimulated by either artificial or natural light [59, 60]. The impacts of various parameters of light and the corresponding photometric metrics and units for the assessment of NIF effects are summarized in Table 1.2. Reviewing this body of knowledge in photobiology, as follows, provides designers with information regarding the NIF effects of light and offers a greater incentive for climate-adapted design.

1.6.2.1 Circadian clocks

The human circadian system refers to the master clock and other peripheral clocks of the human body [79]. Circadian clocks can be reset by and synchronized by environmental time cues or “zeitgebers” (i.e., time giver or synchronizer). The light/dark cycle generated by the local photoperiod is considered as the most effective synchronizing factor [32, 43]. From the perspective of biological mechanisms, eyes exclusive transmit IF and NIF information of incident light [13]. Studies show that the ipRGC, as one type of non-classical photoreceptors located in the retina, are responsible for absorbing and transmitting the NIF information related to light [71, 80]. The ipRGC are first known as melanopsin-expressing retinal ganglion cells (mRGCs) [66]. They contain a photopigment called melanopsin with a spectral sensitivity curve that peaks in the short wavelengths of visual light at about 480 nm, also called blue light (see Figure 1. 6-A) [81-83]. After absorbing blue light, the ipRGC send neural signals to the suprachiasmatic nucleus (SCN) through the retino-hypothalamic tract where the master body clock is located [17, 84]. The SCN initiates and controls many biological rhythms in human body such as the sleep/wake cycle, core body temperature (CBT), and heart rate variability [13] to name a few. It is remarkable that the endogenous master clock in the SCN, as well as other peripheral clocks, runs intrinsically close to, but not exactly, 24h or one day without the intervention of zeitgebers [17, 32, 71].

In the presence of an external light-dark cycle, the circadian system actively adjusts individuals' diurnal behaviors and the temporal rhythm of biological functions to the local time and environment, in particular the photoperiod [85, 86]. The best way to characterize the circadian rhythm is to monitor the pineal melatonin secretion, CBT or cortisol secretion cycle [32, 43, 86]. Melatonin is claimed to be a robust circadian marker due to its small variability. Melatonin is a darkness hormone that signals nighttime that will yield to drowsiness and sleepiness diurnal species such as human. Melatonin secretion occurs from around 7:00p.m. to about 07:00a.m. (so-called biological night) with a peak near 03:00a.m.-04:00a.m. for humans [13, 79]. Furthermore, the circadian rhythm and melatonin secretion have been reported to be highly sensitive to blue light. Their spectral sensitivity functions peak at $C(\lambda)$~460 nm and $V^z(\lambda)$~480 nm, respectively (see Figure 1.6-B) [66, 68, 72]. This can reset or delay/advance the phases of the circadian system and melatonin secretion by modifying several parameters of light [87] such as the quantity (dim/bright/light dose) [88], spectrum (blue wavelengths) [89], time (morning/afternoon/night) [84], duration (hourly) and history (weekly/monthly)[43] of the light that individuals are exposed to. Figure 1.7 shows some patterns of the impacts of light parameters on different circadian rhythms, as proposed by previous researchers. More details on the impacts of different parameters of a light source on the circadian system are presented in Table 1.2. However, many difficulties arise in analyzing the circadian effects of a light source in the actual conditions of an existing building.

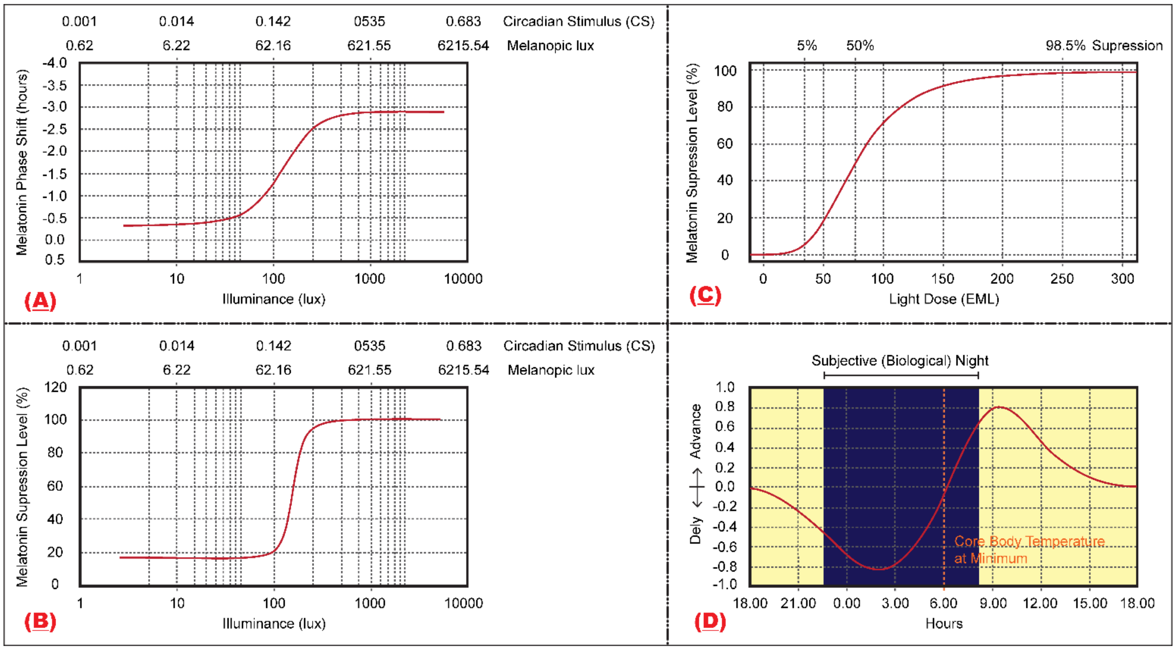


Figure 1. 7. (A) Melatonin phase shift and (B) melatonin suppression versus illuminance, melanopic lux and circadian stimulus (CS) for a single 6.5-hour exposure of white light at the cornea from a 4100K fluorescent lamp during biological night. Figures are modified and reproduced based on the data given by DiLaura et al. [13] and publicly released calculators for melanopic lux and circadian stimulus conversion by Lucas et al. [90] and Rea & Figueiro [91], respectively. (C) Regenerated figure of melatonin suppression level versus light dose (EML) based on Konis [57]. (E)) Regenerated figure of circadian phase response of the pacemaker to time of exposure to optical radiation given by DiLaura et al. [13]

Table 1. 2. The NIF effects of different parameters of optical radiation on humans and corresponding photometric units and equipment [13, 66, 68, 74, 76, 89, 92-95]

Light parameter	Impact	Metric	Unit	Equipment
Quantity (See Fig. 7)	• Human circadian pacemaker phase shifts in response to relatively low levels of a broadband spectrum white light source (approximately 100 lux [10 fc] at the cornea) • The phase-delay resetting response of the body clock saturates at ~600–1000 lux (~60–100 fc) at the cornea. • 50% of the maximum resetting response occurs with ~100 lux (~10 fc) at the cornea.	Illuminance Luminance Melanopic	lux Cd/m2 Melanopic lux EML CS, CL_A	Illuminance and Luminance meter Melanopic meter HDR image
Spectrum	• Circadian and melanopic sensitivity curve peaks in the short wavelength portion of the visible spectrum (blue light) at nearly 460 and 480 nm wavelengths. • Red light does not suppress melatonin. • Long-wavelength (red) light and short wavelength (blue) light increased alertness at night.	Wavelength Color temperature Spectral power distribution	nanometer Kelvin W/m2 × sr × nm W/m2 × nm	Spectrometer Spectrophotometer Colorimeter or filtered radiometer Spectroradiometer
Timing (See Fig. 7)	• The timing of any optical radiation exposure as well as natural photoperiod influences the direction and magnitude of body rhythm phase-resetting effects, in particular circadian entertainment. • Exposure in the morning can shift the circadian pacemaker timing earlier (i.e., advance the clock phase); exposure in the evening can shift the pacemaker timing later (that is, delay the clock phase). • Optical radiation exposure has a maximum pacemaker shifting effect when it occurs during the biological night. Exposure is less effective during the biological day. • Exposure to short wavelengths at night (or bright light) in conjunction with darkness (or less-bluish light) during the day facilitates adaptation to night work.	Time	second	–
Duration	• The NIF effects depend on the duration and pattern of optical radiation exposure. • A daily 3-h exposure to 5000 lux (500 fc) at the cornea was as effective as a 6-h exposure for adaptation to an experimental night shift. • A 1-h exposure to 10,000 lux (1000 fc) from a polychromatic light source at the cornea has approximately 45% of the phase response curve (PRC) amplitude of a 6.7-h exposure to the same optical radiation.	Time	second	–
Spatial distribution	• The ipRGCs are distributed throughout the entire retina, being denser in the supero-temporal pole. • Unlike the visual system, NIF photoreception does not require precise spatial resolution of optical radiation because it concerns changes in ambient irradiance.	Measuring the luminous intensity distribution, luminance distribution, luminous flux or spatial color distribution	W W/m2 W/sr × m2	Goniophotometer CCD-based camera systems HDR image with calibrated digital camera
Adaptation	• The photic history (from the preceding hours, days and weeks) affects the sensitivity of the human body clock to optical radiation at night. • The higher the exposure to optical radiation during the day, the lower the human circadian system's sensitivity becomes to optical radiation at night.	Time	second	–

The development of a framework for the circadian assessment of lighting and daylighting systems in the built environment with actual photoperiod efforts is ongoing. Thus far, some functions along with their corresponding calculators have been developed such as 'Melanopic lux' ($V^z(\lambda)$) [66, 90], Equivalent Melanopic Lux (EML) [93],'Circadian Light' (CL_A), and 'Circadian Stimulus' (CS) [94, 95],[2] which can be applied to different light sources. Studies in this area have been conducted in controlled laboratory settings. The applications and contributions of such studies in design fields are severely restricted due to the complex nature of the real world. A few published studies cover this gap by employing new metrics and developing new analysis methods. In this regard, the International WELL Building Institute [93] released a human-centered building standard in response to human well-being needs. WELL provides some recommendations for lighting design in terms of IF and NIF effects. WELL proposes the EML function to calculate the melanopic lux of a light source [90, 93]. WELL offers no specific analysis method. The time, duration, distribution and photopic history of the exposure to light has been neglected in this function. Meanwhile, it is argued that no scientific foundation supports the relationship between the NIF effects and 'melanopic lux' of light [91][3]. Moreover, Konis [57] developed a spatial assessment method to quantify and map the frequency of the circadian-effective daylight stimulus. This method was developed based on the EML function. Hence, it has the limitations of EML[4]. The method also needs further empirical studies to confirm the assumptions of the relationship between exposure to various stimulus frequency levels and circadian impacts. *Andersen, et al. [96], and Mardaljevic, et al. [97] also developed a photobiology-based lighting model[5].* This model was developed to predict the magnitude and direction of the circadian effects by measuring the vertical illuminance at the eye level, light source spectrum, and timing. As a major limitation, this method has only been used to analyze the circadian effects of three types of

[2] *After the publication of this chapter, CIE released several documents regarding melanopic units of lighting including 'The alpha-opic Toolbox v1.049'. Next chapters are referred to such documents and units.*

[3] *A member of the thesis jury also highlighted that: "Tekieh et al. uses melanopic-weighted irradiance to drive their functions, which is linearly proportional to melanopic illuminance. (refer to [Tekieh T, Lockley SW, Robinson PA, McCloskey S, Zobaer MS and Postnova S. Modeling melanopsin-mediated effects of light on circadian phase, melatonin suppression, and subjective sleepiness. J Pineal Res 69 (2020) e12681]". The author should remind that this paper is published after the publication of this chapter.*

[4] *A member of the thesis jury also highlighted that: "Amundadottir et al. (2017) also points to that the NIF system has varying sensitivity to EML, which is not a great basis for saturation methods like Konis [57] and WELL [93]. (refer to [Amundadottir, Maria L., et al. A human-centric approach to assess daylight in buildings for non-visual health potential, visual interest, and gaze behavior. Building and Environment 113 (2017): 5-21.])"*

[5] *This sentence is revised to use in the thesis based on the jury's comments.*

skylights including D55, D65 and D75 [96, 97][6]. Furthermore, high dynamic range (HDR) imagery technique has recently been developed to analyze both IF and NIF effects of light [76]. The HDR image is mapped to the luminance distribution of a space by capturing multiple digital images of the scene [75, 76]. HDR imagery techniques can provide a spatial distribution of luminance based on RGB value of pixels [75]. In a similar way, the circadian effects of the scene can be calculated through HDR images [76]. It is also possible to determine the illuminance, CIE XYZ and CCT of the scene based on the RGB values of each pixel [76]. However, this method has several limitations. For example, it requires extensive calibration and post-processing steps. Meanwhile, the photometric information is highly dependent on matching the camera response and the photopic function [75, 76]. Overall, designers still have no effective and practical model to actively consider and evaluate the circadian effects of light in a space. Thus, further studies are required to consider and analyze the circadian effects in buildings with an actual photoperiod. Considering the challenging lighting conditions of the North, special efforts should be made for such climates. Meanwhile, lighting scenarios should be developed to adapt the requirements of human beings to daylight availability, outdoor views, and circadian synchronization to light/dark cycles.

1.6.2.2 Alertness and performance

Investigations on individuals' alertness and performance under different light doses, quality and timing have been done as part of NIF aspects of light. It is claimed that alertness and performance are influenced through ipRGC light detection [83]. Exposure to light at night and under a high sleepiness state causes an increase in alertness and improves performance on some cognitive tasks [83, 85]. In terms of light spectrum, objective and subjective alertness levels also show an increase to either blue- or red-enriched light impulse [92]. Many studies have been conducted to explore the impacts of different parameters of light on alertness and performance, as stated in Table 1.2. However, studying these issues is an open-ended effort especially in response to lighting design adjustments in the buildings and the real-time photoperiod. No guideline has yet been offered to adapt light in the built environment for the purpose of alertness and performance increase.

[6] *A member of the thesis jury also highlighted that: "Another shortcoming of this method is that if you have reflective/transmissive surfaces with different Melanopic/Photopic properties, the method doesn't really make allowances for that and in a strict interpretation could result in the same outputs."*

1.5.2.3 Light-related health issues

Diseases and disorders due to insufficient or inappropriate light have become a serious concern especially in Nordic climate zones. Human- and nature-friendly lighting design of man-made spaces have been claimed to be capable of confronting these issues. However, the existing lighting standards for buildings require further development to be appropriate for humans and nature-friendly [57]. Some of the light-related diseases and disorders are sleep-wake disorder and insomnia, seasonal affective disorder (SAD), depression, eye diseases, skin diseases, weight gain, cardiovascular disease, cancer and eventually death [13, 78, 79, 84]. In the few past years, light therapy has been developed in order to cure and mitigate these light-related health problems [13].

1.7 Structural analysis of biophilic design

The current patterns of biophilic design present several strengths and weaknesses to efficiently fulfil design values and human needs. The main goal of biophilic design is to bridge the gap between people and nature in the built environment [3, 98]. As claimed by Gullone [20], Hartig et al. [48], and Ryan et al. [25], biophilic design restores and improves human health and well-being, both physiologically and psychologically. Hence, using a hierarchy of needs provides a clear image of how biophilic design satisfies and fulfils this goal. As depicted in Figure 1.8, the suggested biophilic design attributes and patterns can be associated with Maslow's hierarchy of needs and interpreted for design. More specifically, Figure 1.8-A & B illustrates Maslow's hierarchy of needs and provides a relevant interpretation for design and biophilia, respectively. The figure is designed according to the published works of Lang [99], Zhang & Dong [100] and Noltemeyer, et al. [101]. Maslow claimed that so-called deficiency needs (D-needs e.g. physiological and biological needs) should be satisfied in order to flourish self-actualization or growth needs (G-needs e.g. cognitive, aesthetics, self-actualization and transcendence needs) and reach the optimal level of functioning [100, 101]. Maslow also explained that an individual level of needs could be simultaneously satisfied or prioritized within a certain period [101]. The conceptual framework of Maslow's pyramid can be developed and adapted for design objectives, as depicted in Figure 1. 8-B [102]. Similarly, it can be claimed that poor designs may partially satisfy needs from different levels without meeting the basic and lower-level needs sufficiently [102]. On the contrary, good designs satisfactorily address the hierarchy of human needs [102].

Considering the hierarchy of needs and design values, the efficiency of biophilic design depends on its contributions towards the enrichment of design and the satisfaction of human needs. These issues are more important and challenging in the extreme cold climates of the North where people mostly stay inside buildings. It can be reasonably argued that the suggested biophilic design guidelines predominantly point out to the lower level of needs. In particular, biophilic design focuses on basic design requirements and on the improvement of human health and well-being. It has just a few indirect outcomes in mid-level needs such as usability and proficiency needs, or even higher-level needs by encouraging to biomorphic forms, complexity and mystery. In this regard, Browning et al. [1] suggest that biophilia is another component of environmental quality such as thermal comfort and daylighting, with the same necessity. In other words, biophilia is recognized as an environmental quality feature that considers human biological health and well-being in design, and that covers the deficiencies of human needs and building performance relationships [1]. This viewpoint has been widely supported and approved by reviewing existing studies of the physiological and psychological impacts of biophilic and nature-oriented design (for example see [1, 19, 20, 25, 48]).

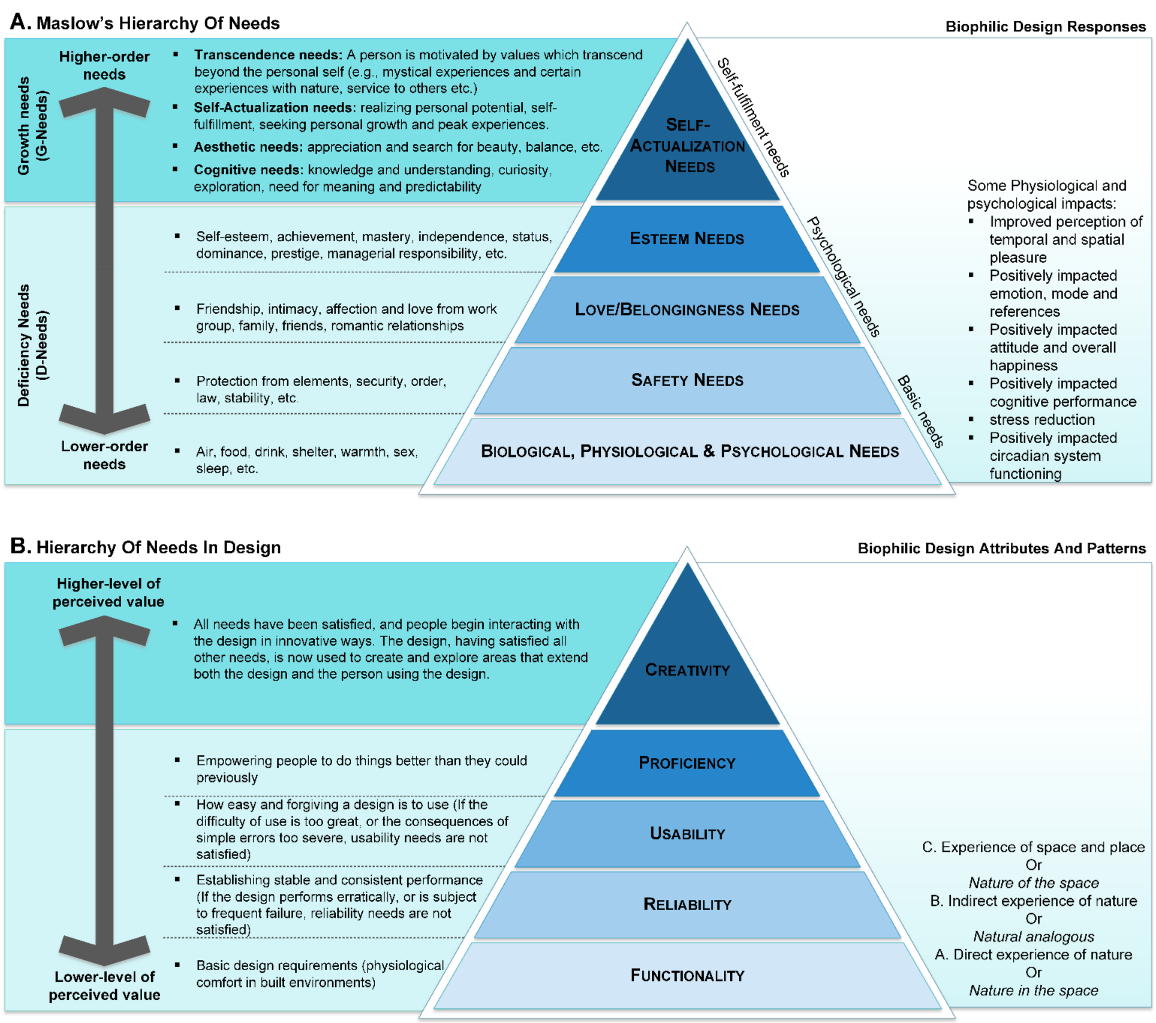


Figure 1. 8. (A) Maslow's hierarchy of needs and (B) interpretation relevant to biophilic design

As a main weakness, the given strategies mainly suffer from the lack of a systemic framework for the intervention and assessment of biophilic qualities from the early stages of the design process until after building execution. It is broadly recognized that the design process includes different stages such as "cognition, analysis, synthesis, design-making, implementation and evaluation" [103]. However, the given biophilic strategies propose no clear systemic intervention in any stage of the design process. This drawback has recently been noticed by some researchers. In this regard, the International Living Future Institute [104] released the 'biophilic design exploration guideline', which includes five steps to design and implement a project by biophilic exploration. In another study, Kayihan et al. [105] attempted to raise awareness of third-year undergraduate architecture students to biophilic theories. Yet, they did not propose any specific design process, intervention, or evaluation mechanism for achieving biophilic design objectives. Thus, designers still meet serious challenges regarding how, when and to what extent biophilic recommendations could be applied in the design process. This limitation is basically attributable to the fact that the biophilic design approach only expresses advantages of nature in built environments.

As an environmental quality, biophilic design or quality does not necessarily relate to any evaluation system. In fact, biophilic qualities have not yet been defined as an index, indicator, or rating system. Meanwhile, several validated indexes and evaluation systems have been developed for airflow, thermal, visual, and acoustical comfort in built environments. Hence, neither designers, policymakers, nor stakeholders have valid and reliable indicators to assess the biophilic qualities required for a space, a building, and a city. Eventually, the proposed design patterns remain in the form of statements or manifests, remote from applications in built environments. Recent attempts have been made towards this issue such as the rating system offered by the International Living Future Institute [106], the assessment system proposed by the International WELL Building Institute [93], the biophilia matrix identification strategy suggested by McGee and Marshall-Baker [107], the biophilic quality index (BQI) [108] offered by Berto and Barbiero, or the analytic hierarchy process (AHP) examined by Sharifi and Sabernejad [98]. The proposed assessment methods and indexes are still far from being comprehensively, productively, and efficiently involved in the design process or the post-occupancy evaluation of spaces. Meanwhile, more subjective and objective experiments and research are needed to confirm the validity and reliability of the methods and indexes offered.

1.8 A plausible hypothesis of adaptive envelopes

This paper calls special attention to building envelopes and adaptation strategies as a promising hypothesis to address the challenges of biophilic design for northern regions. Building envelopes *could act as*[7] an in-between and transient space that link humans and their surrounding environment. Building envelopes stand as a promising avenue to address the human-nature relationship. Meanwhile, both nature and humans have been characterized as dynamic, adaptable, and evolvable systems that change temporally (annually, seasonally, or hourly) and spatially (geographical /latitudinal position), as depicted in Figure 1.1. Hence, building envelopes should be designed as dynamic, adaptable, and evolvable systems in response to the environmental conditions and human needs. In fact, building envelopes should be adapted to dynamic climate variations, particularly for the critical solar radiation and temperatures in extreme cold climates. Adaptive building envelopes could be developed to fulfil human needs and meet biophilic design criteria. In this regard, adaptive building envelopes have been identified as systems with intelligent, repeatable and reversible modification abilities for some of their functions, features or behavior over time, which adapt and modify the overall building performance according to dynamic environmental conditions [109]. The knowledge of adaptive envelopes and buildings is growing significantly. The idea of buildings that adapt to different contexts and actors in order to achieve satisfactory, reliable and sustainable responses has become the focus of worldwide discussions in recent years [103, 110]. Different adaptation strategies have thus far been proposed such as climate adaptive building shells [109], double skin façades [111], and climate responsive shells and forms [112, 113]. As shown in Figure 1.9, several practices of such adaptive buildings and envelopes have been built around the world for example the Headquarters of the Swiss Federal Railways (Bern, Switzerland), Sharifi-Ha House (Tehran, Iran), Arab World Institute (Paris, France), Kiefer Technic Showroom (Bad Gleichenberg, Austria), Al Bahar Towers (Abu Dhabi, UAE) and University of Arizona Cancer Center (Phoenix, AZ, USA). As these projects show, adaptive buildings and envelopes exist for different purposes and climates.

[7] *This sentence is revised to use in the thesis based on the jury's comments.*

Case	Headquarters of The Swiss Federal Railways	Sharifi-Ha House	Arab World Institute	Kiefer Technic Showroom	Al Bahar Towers	University of Arizona Cancer Center
Location	Bern, Switzerland	Tehran, Iran	Paris, France	Bad Gleichenberg, Austria	Abu Dhabi, UAE	Phoenix, AZ, USA
Function	Office	Residential	Cultural	Office	Residential tower	Medical/ Educational
Climate	Cold	Cold	Temperate	Temperate	Hot & humid	Hot

Figure 1. 9. Examples of adaptive buildings and envelopes

Adaptive envelopes should be developed to optimize biophilic qualities and to fulfil the photobiological needs of people in extreme cold climates. Previous studies asserted the economic and environmental effectiveness of adaptive buildings in terms of indoor air quality, visual comfort, acoustic performance, energy aspects and CO_2 emissions [114, 115]. No investigation has yet been conducted regarding the efficiency of such adaptive envelopes in extreme cold climates and the improvement of human NIF responses. Therefore, developing adaptive envelopes to reconcile occupants' photobiological needs with natural conditions hypothetically constitutes a promising solution to the serious lighting challenges in northern regions. Such adaptive envelopes are responsible for providing daylight and views to the surrounding environment, which comes with many difficulties to deal with in extreme climatic conditions. These adaptive envelopes should also detect outdoor environmental conditions and process the essential qualities and parameters related to photobiological and biophilic performances. Such envelope systems should optimize the utilization of natural environments based on lighting adaptation scenarios. The intended adaptive envelopes should eventually improve the well-being of occupants regarding the IF and NIF effects of light inside buildings. Adaptive building envelopes should be the subject of future studies. Currently, the authors of this paper are focusing on the development of such envelopes for buildings located in the north of Quebec, Canada, as part of the Sentinel North Strategy conducted by Laval University.

1.9 Conclusion

This paper aims to propose biophilic design as a potential solution for the challenging climatic conditions of northern regions, especially regarding daylighting availability. The paper discusses the shortcomings of the suggested strategies in response to (1) their implementation in extreme climates; (2) local photoperiods and the photobiological needs of people; and (3) active and systemic interventions, contributions and evaluations in the design process and post-occupancy. Regarding the first shortcoming, the severe condition of the north demands more efforts to develop appropriate and practical biophilic design patterns and attributes. This should be combined with an efficient response to the respective environmental factors and parameters, in particular solar radiation and photoperiods. Therefore, developing and employing the biophilic design approach in this extreme cold climate will potentially yield significant human well-being and environmental benefits.

Furthermore, biophilic design emphasizes daylighting, natural patterns, and cycles, view to nature and human-friendly lighting. Meanwhile, the light/dark cycle is identified as the most important environmental cue or zeitgebers that triggers many biological and socio-cultural events. The photoperiod shows a huge seasonal variation in the northern latitudes. Hence, the availability and accessibility to daylight come with difficulties in such regions. This paper draws attention to this situation and to the importance of light and local photoperiods for human well-being and health. The paper elaborates on this perspective in more detail by critically reviewing the knowledge of lighting design and photobiology. In this regard, it discusses the IF and NIF visual responses of humans to light. It also clarifies that the lighting design and control systems in buildings have undeniable biological effects on people, especially for those who live in sub-Arctic climates. Subsequently, the paper emphasizes the lack of knowledge in lighting design to fulfil the photobiological needs of people and meet the objectives of biophilic design. This issue points to the second deficiency of biophilic design guidelines in Nordic regions. More specifically, the NIF effects of light have become the missing link between human needs and lighting design standards. Researchers have recently made efforts to use the knowledge of photobiology to develop several metrics (such as Melanopic lux, EML CS and CL_A) and evaluate the NIF effects of light in built environments. Yet, this area of study demands further development in terms of evaluation systems, metrics, contributions to lighting design and the fulfilment of biophilic needs. Furthermore, accessibility to nature scenes, as a basic human need subjected by biophilic theory, has direct impacts on building lighting strategies and human IF and NIF perception of light. Hence, this issue should also be considered in the development of lighting standards and adapted for the harsh climate of northern territories.

Aiming to promote human-nature relationships, the last shortcoming of biophilic design calls for the development of a design process framework as well as an assessment system. The existing guidelines have offered no systemic framework by which designers can actively and consciously utilize biophilic recommendations in their design. Moreover, no assessment or rating system has been proposed to measure the quality or quantity of biophilia in the building. Therefore, the biophilic quality of the building is depended on the skills, experiences, and intuition of designers towards translating and applying the recommendations into the design. Thus, future studies should focus on this aspect.

Finally, the paper identifies the promising hypothesis of adaptive building envelopes. More specifically, the adaptive envelope system should be developed to optimize the biophilic quality and photobiological performance of buildings in the North through lighting adaptation scenarios. In fact, building envelopes stand as a physical in-between and transient system that connect nature, humans, indoor and outdoor environments. They also provide a meeting ground for climate, biology, design and technology. Therefore, they should be developed to appropriately mediate the exterior conditions for human health and delight. Adaptive envelopes are hypothetically capable of offering mechanisms for the adaptation of buildings to human needs and natural conditions. This idea should be developed in future studies.

1.10 Acknowledgment

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Chapitre 2: Biophilic, photobiological and energy-efficient design framework of adaptive building façades for Northern Canada

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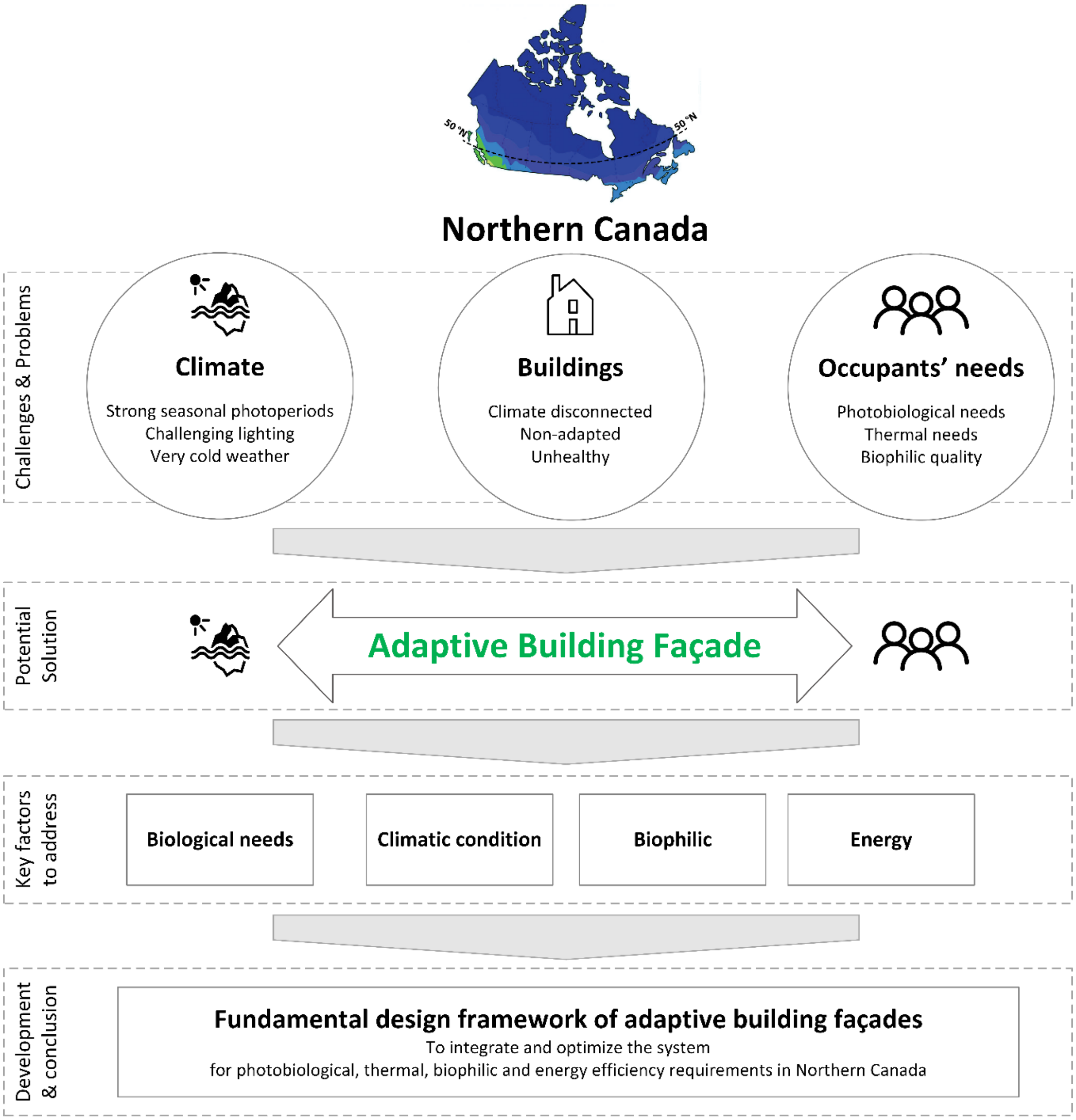
Graphical Abstract



2.1 Résumé

Cet article développe un cadre de conception intégré pour les façades adaptatives des bâtiments (ABF) afin de répondre aux besoins photobiologiques et thermiques des occupants, aux facteurs biophiles, aux besoins énergétiques et aux caractéristiques climatiques dans le nord du Canada, c'est-à-dire à proximité et au-dessus de 50°N. L'article discute de l'importance des facteurs biophiles et photobiologiques et des ABF pour améliorer la santé des occupants et les relations entre l'homme et la nature ainsi que pour remédier au caractère extrême du climat dans le nord du Canada, où les bâtiments non adaptés pourraient affecter négativement le bien-être des occupants. L'article démontre que les ABF existants doivent être développés pour les applications dans le Nord en termes (i) de structure physique et de configuration des éléments, (ii) de conception de panneaux solaires pour répondre aux besoins photobiologiques et biophiles, (iii) de développement de scénarios d'adaptation de l'éclairage pour répondre aux besoins biophiles et photobiologiques ainsi qu'aux photopériodes locales et aux questions énergétiques, et (iv) de qualité biophilique totale pour l'accessibilité aux motifs naturels. Le cadre des ABF a été élaboré en trois phases: (1) le traitement des données environnementales, (2) la production de scénarios d'adaptation, et (3) la mise en œuvre des scénarios d'adaptation. La recherche a abordé les enjeux majeurs de toutes les phases qui doivent être étudiés plus en profondeur, en particulier le développement de scénarios d'adaptation de l'éclairage horaire/quotidien/saisonnier. L'article développe une méthodologie paramétrique holistique pour intégrer et optimiser les principales variables de conception des composants d'ABF.

2.2 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.

2.3 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.

2.4 Importance of the study

2.4.1 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 [18, 19, 25]. 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 [21, 116-118]. Biophilic design guidelines offer several recommendations [1, 3] which could be adjusted to promote human-nature relationships in the extreme cold climate of Northern Canada [119, 120]. People spent ample time in buildings in such climates, thus the biophilic approach has greater benefits [35, 36]. 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 [121] 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 [122]. As stated by photobiological studies, light triggers many reactions in the human body, through the visual system [123, 124]. Human visual system responses to incident light have two components, namely image-forming (IF) and non-image forming (NIF) [13, 50, 125]. The IF responses result in image formation and the sense of vision [13, 50] whereas the NIF responses refer mainly to the light effects on circadian clocks (also known as body clocks) [17, 71, 96], alertness and performance [83, 85]. Human circadian clocks need to be entrained nearly, but not exactly, every 24 hours [17, 71, 96]. 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 [32, 43, 126]. 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 DiLaura, et al. [13], Khademagha, et al. [65], Parsaee, et al. [119], Refinetti [123], CIE [125], Berman and Clear [127], Khademagha, et al. [128]). Occupants' IF and NIF responses/requirements are different regarding hourly/seasonally photoperiods and different activities in the building [129-131]. A proper intensity and chromaticity of light at the right time must be provided to occupants [12, 125]. NIF responses of occupants have recently been addressed in the context of built environments [61, 65, 125], whereas the IF responses have been widely studied [12, 119, 125]. Lighting guidelines and standards of North America have been developed for IF needs and negligible attention is given to NIF needs [13, 50, 58]. Neglecting NIF effects causes serious light-related diseases and disorders such as desynchronized circadian clocks, sleep problems, seasonal affective disorder (SAD), non-seasonal depression, [125] which have extensively been reported in high-latitude regions [41-43, 132].

2.4.2 Climatic challenges in Northern Canada

Buildings must provide the 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 [30] (see Figure 2.1-a). Climatic features drastically change by moving towards high latitudes and sub-Arctic regions of Canada [30, 33, 133] resulting in challenging living and working conditions [39, 134]. Seasonal photoperiods and solar radiation, the most influential factors on the climate and human lives [13, 31, 32], could change from a few hours of daylight in the winter to almost no-darkness during the summer in a high-latitude Canadian cities such as Cambridge Bay, Nunavut, Canada [69.1°N] (Figure 2.1-b). As depicted in Figure 2.1-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 [31, 33]. In such an extreme climate, Northern population has forced to spend a considerable time, more than 90%, inside buildings [35, 36]. 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 [34, 135]. 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% [136, 137] (see Figure 2.2). 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 [1, 3, 11, 12]. 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.

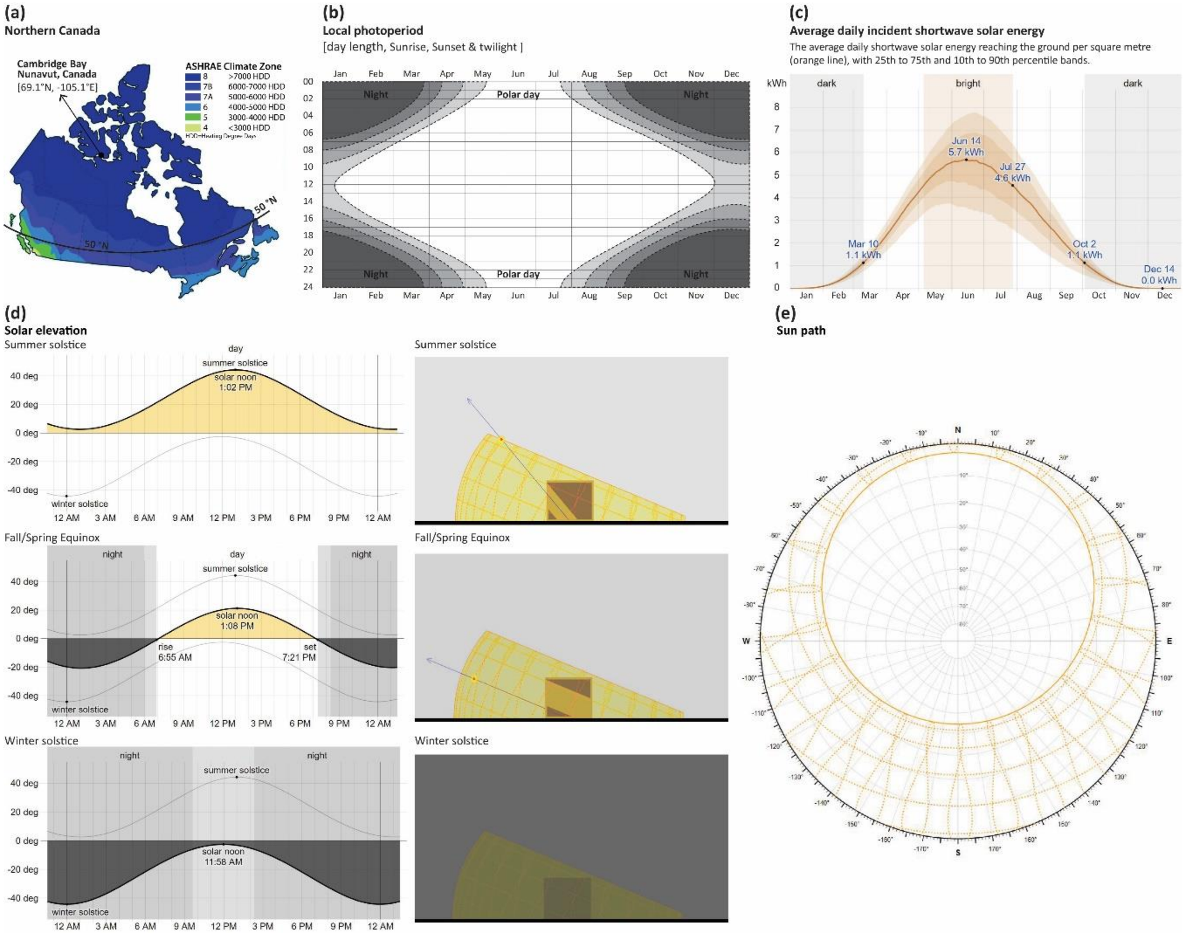


Figure 2. 1. (a) Northern Canada located near and above 50° N categorized into ASHRAE climate zones 7 and 8 [30]. Lighting features of the climate in Cambridge Bay, Nunavut, Canada [69.1°N], including the (b) seasonal photoperiod and day/night length sun path (c) average daily solar energy (d) solar elevation in the summer and winter solstices and spring/fall equinox and (e) sun path geometry (figures are derived from weather spark [46] and online tools offered by Marsh [47])

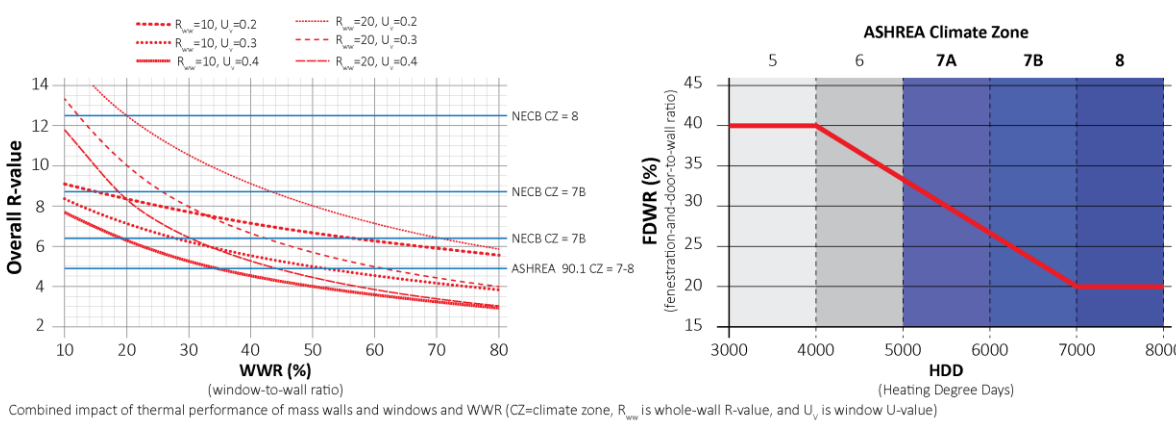


Figure 2. 2. National Energy Code of Canada for Buildings' (NECB) recommendations for the WWR, FDWR and R-value for Canada climate zones 7 and 8 corresponding to northern regions (retrieved from NRC [136], Straube [137])

2.4.3 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 [138-140]. The colour temperature of received light at individuals' eyes, one of the influential parameters in NIF responses [65, 141, 142], can be significantly manipulated by openings, spaces' elements and surfaces' materials, textures and finishing [13, 139, 142, 143]. The façade system, particularly, plays a key role in the development and design of such healthy climate-responsive buildings in Northern Canada [144, 145]. 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 [146-148]. Façade systems affect indoor environmental quality and control accessibility to the surrounding environment, natural cycles and daylighting [146, 149, 150]. 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 [120, 151].

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 [103, 110, 152]. 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 [133, 153]. In this regard, adaptation strategies have, evidently, been appeared in vernacular architecture of different countries and climates like China [154], Vietnam[155], Japan [156], Iran [53, 152], Africa [157]. Adaptation strategies have also been employed in the vernacular settlements of Nordic people in extreme climatic conditions [37, 38, 158-162]. 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 [109], responsive building envelopes [150], intelligent façades [163], advanced integrated façades[164], smart façades [165], double skin façades [111], kinetic façades [166], biomimetic building skins [167], climate responsive shells and forms [112, 113] and adaptive façades with movable insulation panels [168, 169]. As presented in Figure 2.3, several buildings have also been designed and built with adaptation strategies for different uses and climates.

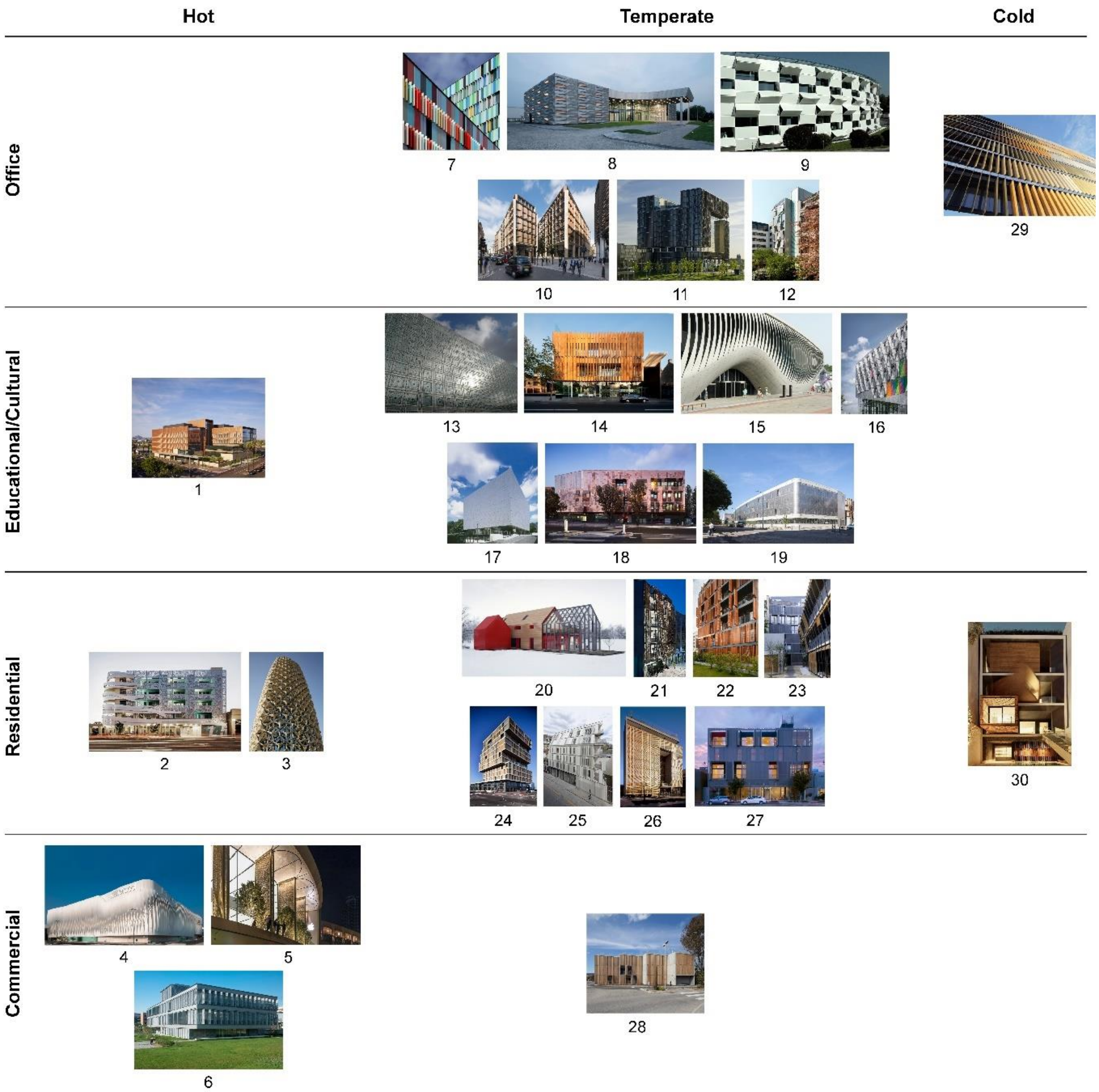


Figure 2. 3. Some examples of adaptive façade strategies built for different building uses in various climates (see Appendix 2.A for further information about these buildings and the courtesy of photos)

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 [147, 170, 171] 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 [109, 172, 173]. These abilities adapt and modify the overall building performance according to dynamic environmental conditions and occupants' needs [109, 172, 173]. ABFs is claimed to offer mechanisms to respond appropriately to occupants' needs and environmental boundary conditions in different climates [172-174]. From this point of view, ABFs have the potential to provide Northern Canadian occupants with a healthy and comfortable indoor environment [40, 119, 120]. This paper contributes to the development of healthy, climate-responsive, and energy-efficient ABFs for the application in Northern Canada.

2.5 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.

2.5.1 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 [121]. 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

2.5.2 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 [30, 121, 175]. Lighting features mainly refer to daylight, seasonal photoperiods (e.g. light/dark cycles) and sun elevation [133, 175]. Thermal features mainly refer to surface and weather temperatures, humidity, wind, solar radiation and precipitation [27, 28]. 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 [171, 176]. 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

2.5.3 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 Browning, et al. [1], Kellert [2], Kellert and Calabrese [3]). Figure 2. 4 displays characteristics of human, nature, buildings and façades with respect to northern-latitude climates and biophilic design recommendations proposed by Browning, et al. [1] and Kellert and Calabrese [3]. No index or metric has thus far been developed to quantify and monitor the biophilic quality of a space [105, 119]. 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[8].
- **Materials:** refer to the consideration of natural or nature-friendly materials.

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[8] *In response to a comment given by a member of the thesis jury, the author clarifies the notion of "nature-friendly" as biomimicry forms or identical colors used in nature. further details are referred to [1] W. Browning, C. Ryan, and J. Clancy, "14 Patterns of biophilic design," T. B. G. LLC, New York, 2014, , [2] S. R. Kellert, "Dimensions, Elements, and Attributes of Biophilic Design," in Biophilic design: the theory, science and practice of bringing buildings to life, S. R. Kellert, J. Heerwagen, and M. Mador, Eds. New Jersey: John Wiley & Sons, 2011, pp. 3-19, [3] S. R. Kellert and E. F. Calabrese, "The practice of biophilic design," Available: www.biophilicdesign.com*

- **Form:** refer to the consideration of biomimicry forms or nature-friendly[9] shapes.

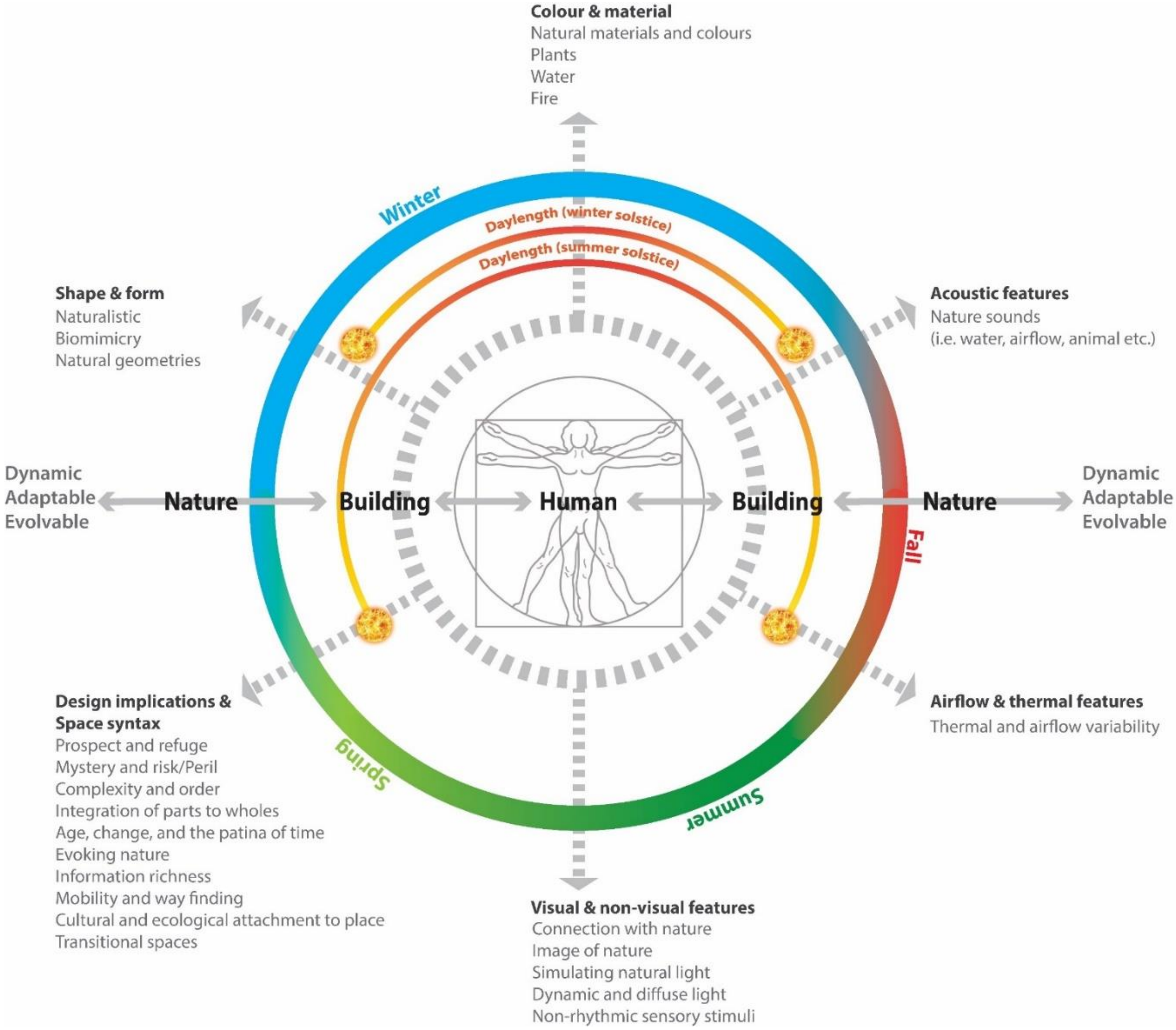

Figure 2. 4. Characteristics of the human, nature and buildings with respect to biophilic design recommendations (based on Browning, et al. [1] and Kellert and Calabrese [3]) and the extreme cold climate of northern latitudes

2.5.4 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 [177-179]. Occupants' behaviour has reciprocal interactions with other factors

[9] *Same as Footnote 8.*

in determining the energy consumption of buildings [180]. 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

2.6 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 2.5, 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.

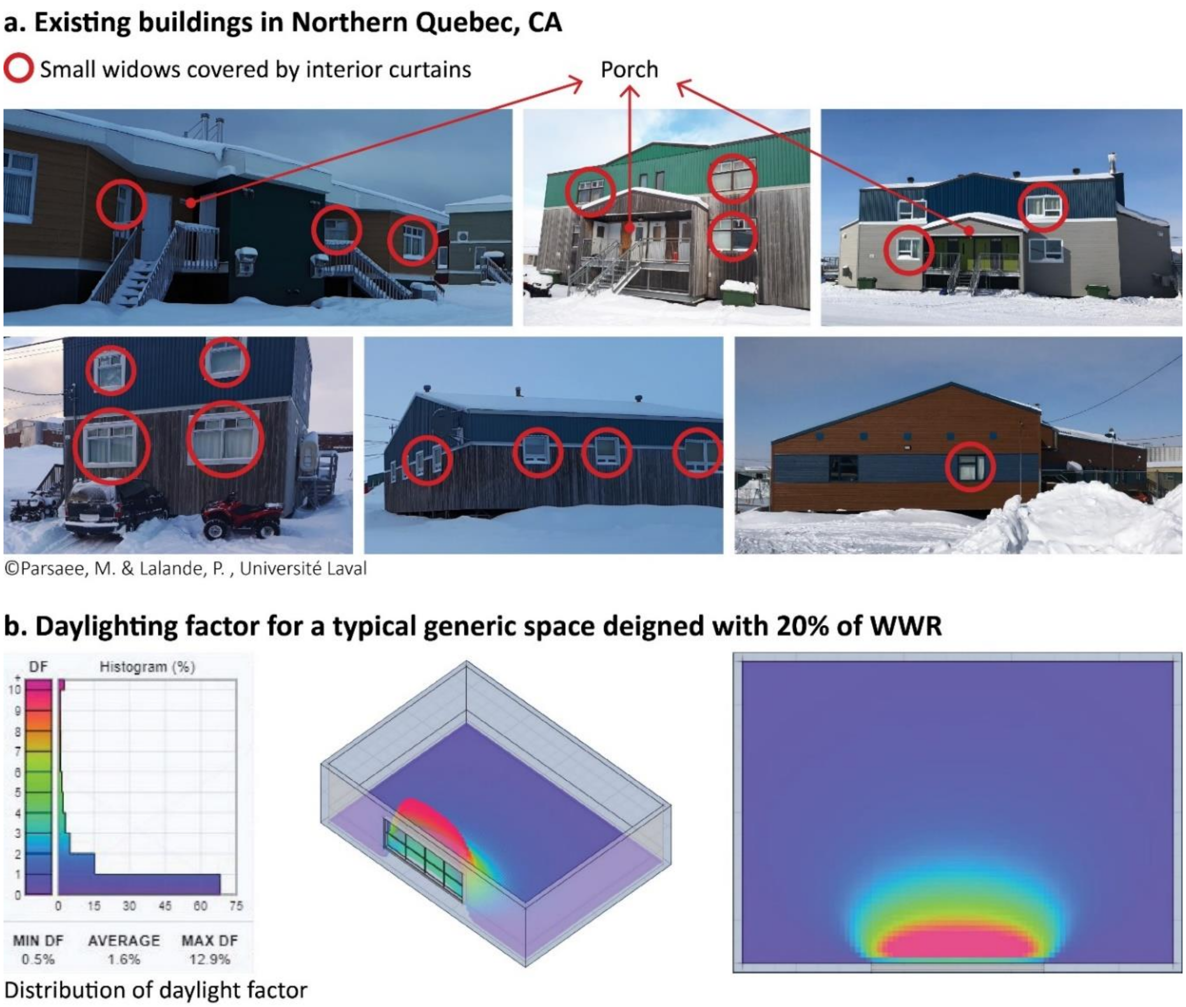

Figure 2. 5. (a) Existing buildings in Northern Quebec (b) daylighting performance inside a generic space in existing buildings in Northern Quebec

In terms of biological needs' factors, *(i) Occupants' photobiological comfort:* 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 [181]. As can be seen in Figure 2.5-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 2.5-b shows the low daylighting performance inside a generic space with a 20% WWR in Northern Quebec. As already been reported [182-185], such unhealthy indoor lighting environments could cause several light-related health issues in high-latitude regions like Northern Canada.
(ii) Occupants' thermal comfort: 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 2.5, 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.

2.7 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 2.1 presents the assessment of some constructed ABFs given in Figure 2.3. 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 mechanisms, behaviours and processes have been developed which are generally include (a) smart, automatic, and high-tech systems, and (b)o 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 emissions. The analysis of energy performance is not available for all 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.

Table 2. 1. An analysis of some constructed adaptive building façades (the sources of information are given in Appendix 2.A.)

	Case	Building Class	Location	Adaptation behaviour	Adaptation process	Adaptation operation	Climate class	Lighting responsive	Thermal responsive	Image forming (IF) effects	Non-image forming (NIF) effects	Thermal aspects	In-between space	View	Colour	Material	Shape and form	Energy efficiency
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

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

2.8 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 2.6. 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.

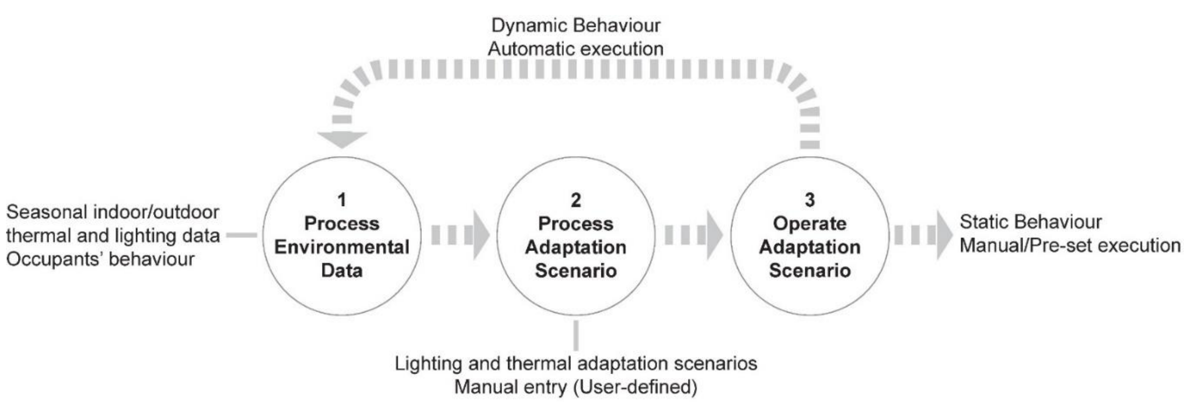

Figure 2. 6. The fundamental concept of an ABF

2.7.1 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 2.B, parts 1 and 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 2.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 2.7). 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 2.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 [186]. Figure 2.7 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.

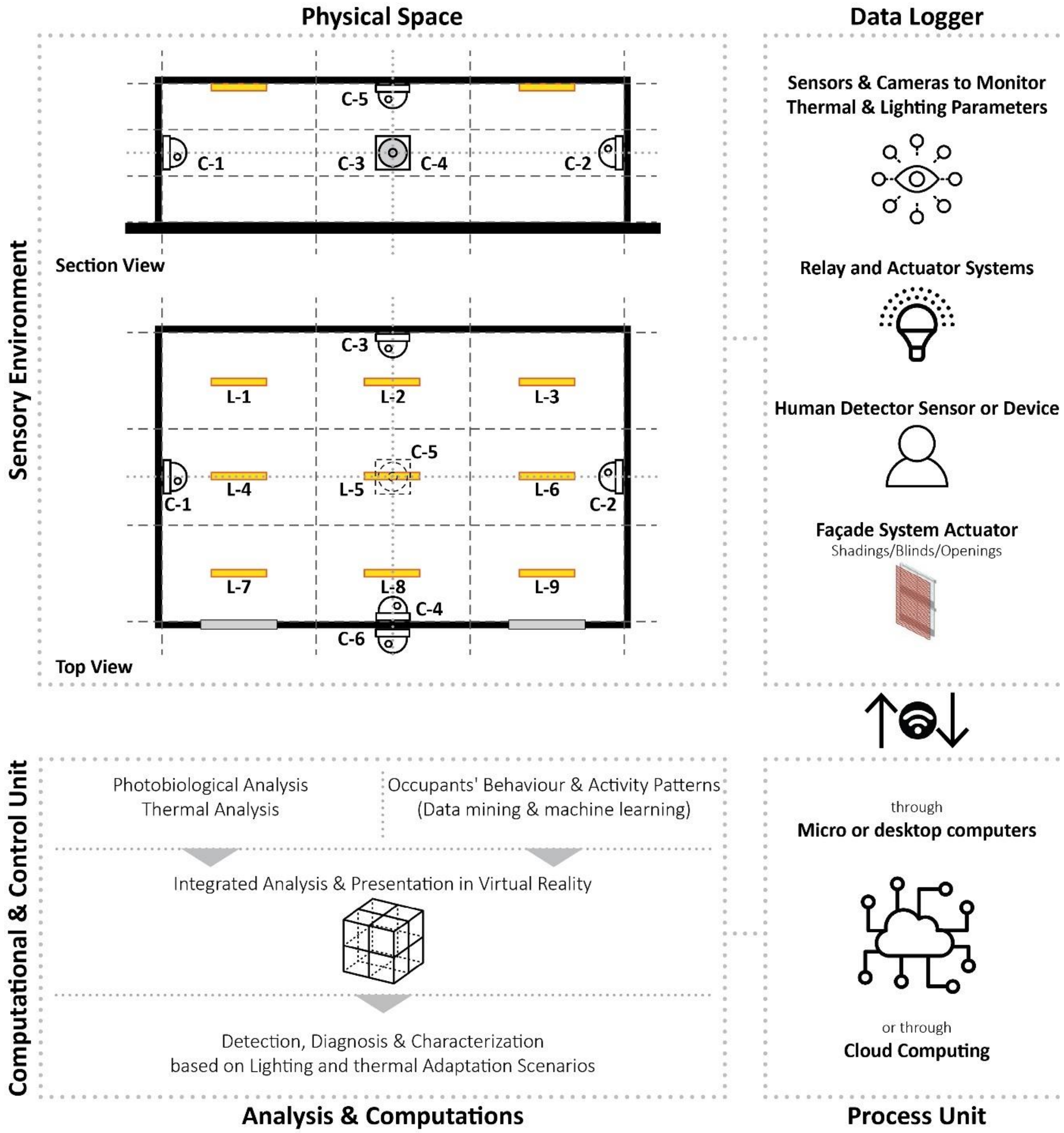

Figure 2. 7. A schematic example of occupancy and environment detection/control system combined with a virtual reality visualization model (developed based on Parsaee, et al. [186])

2.7.2 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 2.1 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 [174, 187].

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 2.8 illustrates the outdoor thermal comfort in the climate context of Cambridge Bay, Nunavut, Canada. As can be seen in Figure 2.8, 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 2.1-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 2.1-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. [168], Montier, et al. [169]). 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.

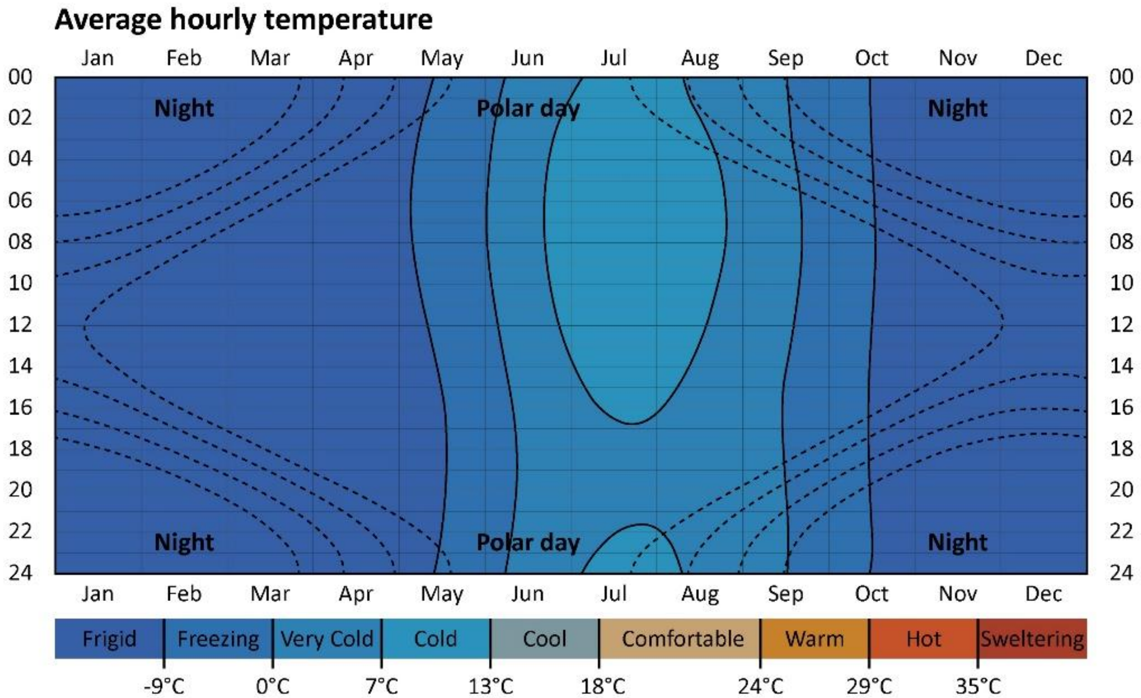

Figure 2. 8. Thermal features of the climate in Cambridge Bay, Nunavut, Canada (retrieved from Weather spark [46], Marsh [47])

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 [188]. 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 [12]. Sufficient darkness or dim light should also be provided when occupants need sleeping or resting in specific spaces such as bedrooms [93]. Meanwhile, sufficient connectivity to natural light and patterns must be accessible to occupants [188]. Table 2.2 summarizes the principal criteria that must be considered in the development of lighting scenarios. Table 2.2 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. 2. Premises and criteria for developing lighting adaptation scenarios (extracted from CIE [12], DiLaura, et al. [13], Konis [57], Lucas, et al. [90], Rea and Figueiro [91], International WELL Building Institute [93], CIE [125], Boivin and Boudreau [189])[10]

	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 plane for visual comfort depending on the task and space function b. 100 lux and l00 EML on the vertical plan at eye level have 50% impacts on melatonin suppression. c. 200 lux and200 EML on the vertical plan at eye level have 90% impacts on melatonin suppression d. A maximum of 50 to 250 lux and EML for a comfortable residential space depending on the task e. Between 250 to 350 lux and EML 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 probably vigilant II. 9:00 to 17:00 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, 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 tunable 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 [190, 191]. Many studies have been conducted to investigate and improve the impact of LED and smart lighting

[10] *Some style and typo errors in this are corrected to use in the thesis based on the jury's comments.*

systems on visual performance, circadian clocks, alertness, cognitive performance, and sleep disorders [191-194]. LED systems are also reported being energy efficient [191]. Despite all these developments, biophilic and photobiological studies have emphasized that the design priority should be given to natural light and connection [1-3, 12].

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 2.9 shows a potential hourly/seasonally adaptation scenario developed for an office space in Kuujjuaq. 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 2.2. 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 Browning, et al. [1], Kellert [2], Kellert and Calabrese [3]). Similar lighting adaptation scenarios could be developed for needs of different building uses and activities such as health care, schools, and residences.

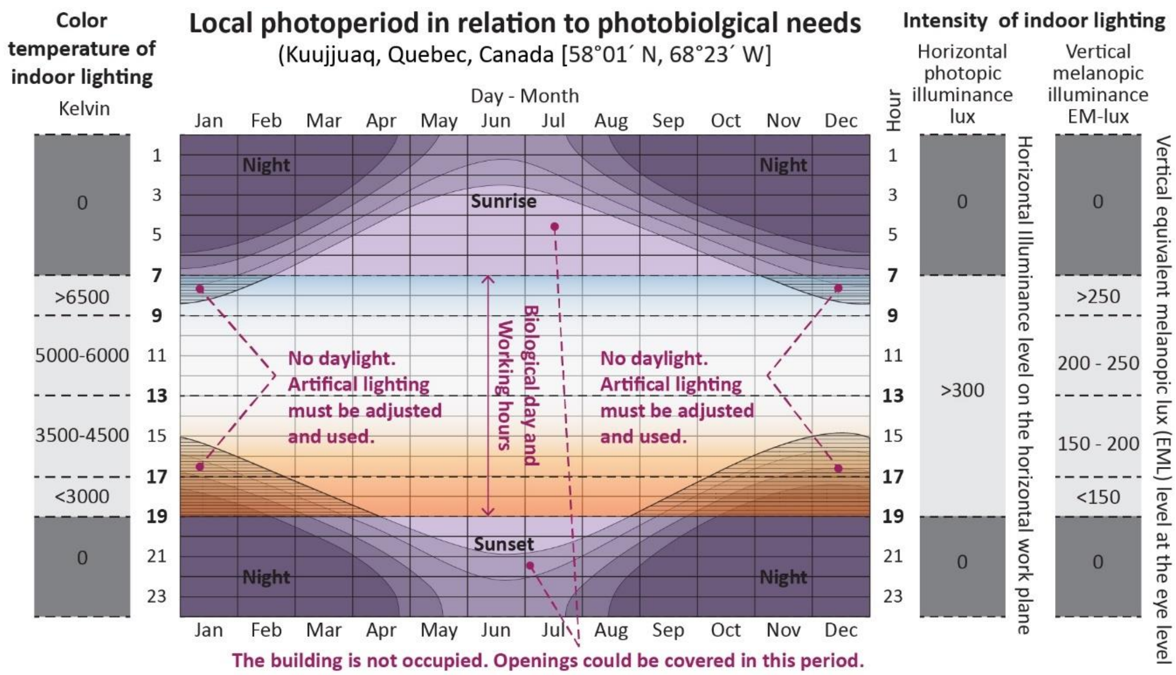

Figure 2. 9. A potential hourly/seasonally lighting adaptation scenario for office buildings in Kuujjuaq, Quebec, Canada.[11]

2.7.3 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 2.1 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.

[11] *This figure is revised to use in the thesis based on the jury's comments.*

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 2.10). 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 [109, 114, 195-202]):
II. **Higher overall biophilic quality by designing an inhabitable in-between space or cavity** (for details refer to [198, 203, 204])
III. **Higher long-term economic benefits** (for details refer to [114, 174])

The components' configuration of MSF systems must be adjusted and optimized for different applications in northern latitudes of Canada. Figure 2.10 proposes several possible configurations of a multi-skin system. Figure 2.10-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 2.10-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 2.10-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 2.10-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 2.10-cases 4 and 5). It can also be located at the interior skin (Figure 2.10-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 2.10-columns c and d present daylighting and solar heat gain behaviours of all cases based on rules of thumb. Table 2.3 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.

Table 2. 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. [114], Barbosa and Ip [197], Poirazis [199], Mingotti, et al. [200], Gratia and De Herde [201], Jiru, et al. [202])

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) has 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.

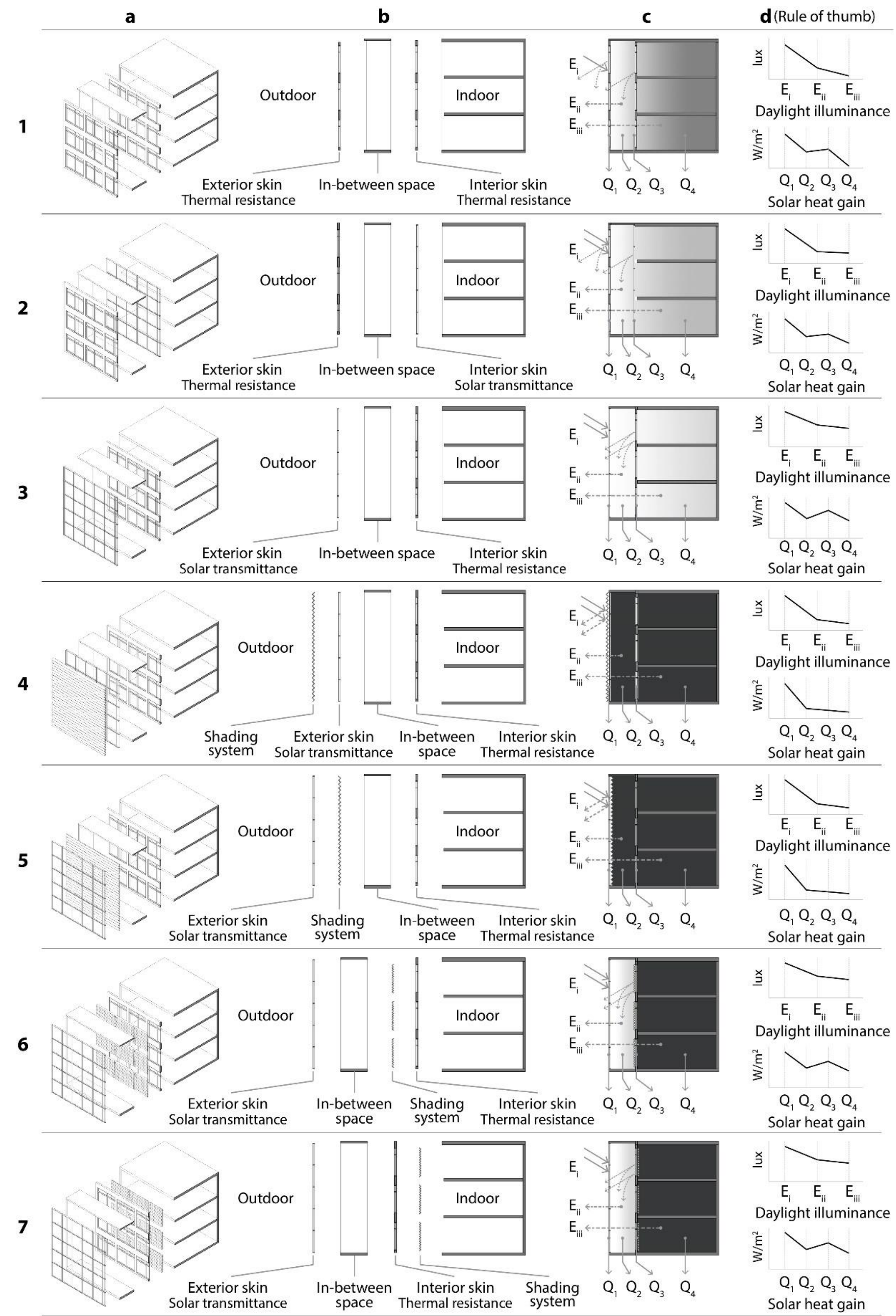

Figure 2. 10. Different components' configurations of a multi-skin façade (MSF)[12]

[12] *This figure is revised to use in the thesis based on the jury's comments.*

Parametric studies could finally be conducted to assess and optimize variables by producing different cases and prototypes. Figure 2.11 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 2.11, 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 2.11, 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 2.B, part-4 for some example studies). One architecturally interesting approach is to use the 'liberty index'[176] 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.

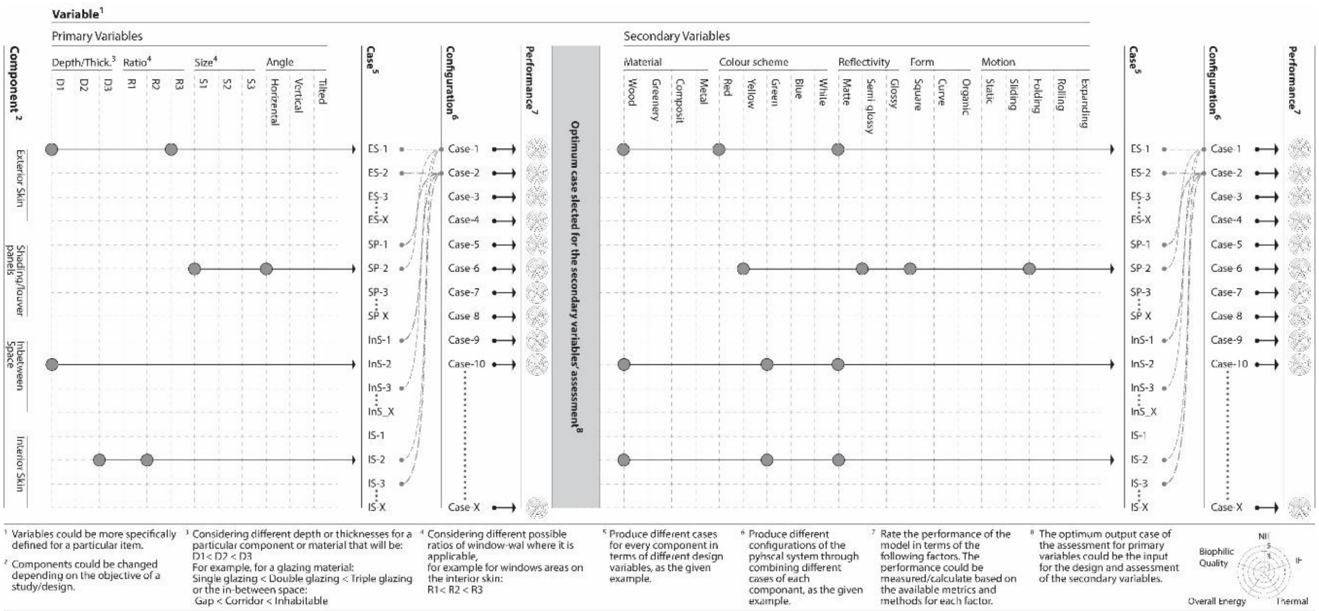

Figure 2. 11. Primary and secondary design variables for the parametric study of ABFs' physical components in terms of photobiological, thermal, biophilic and energy factors

2.9 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.

2.10 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).

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2.12 Appendix 2.A

Table 2. 4. The sources of information for Table 2. 1 and photo courtesies of Figure 2. 3

	Information source	Photo courtesy
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4	https://www.archdaily.com/270592/al-bahar-towers-responsive-facade-aedas?ad_medium=gallery	© Christian Richters on https://www.archdaily.com/510226/light-matters-mashrabiyas-translating-tradition-into-dynamic-facades
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11	https://www.architonic.com/en/project/jems-architekci-wilanowska-housing-complex/5100249	© Juliusz Sokolowski on https://www.architonic.com/en/project/jems-architekci-wilanowska-housing-complex/5100249
12	http://housingprototypes.org/project?File_No=FRA023	© http://housingprototypes.org/project?File_No=FRA023
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30	https://www.archdaily.com/522344/sharifi-ha-house-nextoffice	© Nextoffice on https://www.archdaily.com/522344/sharifi-ha-house-nextoffice

2.13 Appendix 2.B

Part 1. Some examples of thermal comfort indicators: PMV (Predicted Mean Vote)[121], PET (Physiological Equivalent Temperature)[205], UTCI (Universal Thermal Climate Index)[206] and SET*/OUT_SET* (Standard Effective Temperature/ Outdoor Standard Effective Temperature)[207].

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

Table 2. 5. Photobiological lighting parameters

Target analysis	Metric and parameter	Sample study	Tools and methods
Image forming (IF) effects	Luminance ratio and distribution	Maskarenj, et al. [208], Inanici [209], Inanici and Hashemloo [210]	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. [211]	Photometer sensors
	Colour temperature, colour rendering and appearance	Aste, et al. [212]	Photometer sensors Spectrophotometer
	Directionality of light	Cantin and Dubois [213]	Simulation
Non-image-forming (NIF) effects	Circadian Light (CL_A) and Circadian Stimulus (CS)	Acosta, et al. [214]	Spectrophotometer Simulation
	Equivalent Melanopic Lux (EML)	Konis [215], Jung [76], Jung and Inanici [216]	A digital Charge Coupled Device (CCD) spectrometer and HDR images taken by a digital camera
	Circadian Effect Thresholds	Amundadottir, et al. [68]	Spectrophotometer
	Melanopic-Photopic ratio (M/P)	Berman and Clear [127]	Spectrophotometer
Daylighting	Daylight Factor (DF)	Lim, et al. [217]	ENMARS TM-203 illuminance loggers
	Daylight Autonomy (DA)	Bian and Ma [218]	The arrangement of photometric sensors to capture illuminance
	Useful Daylight Illuminance (UDI)	Nabil and Mardaljevic [219]	Simulation
	Daylight Coefficient (DC)	Yoon, et al. [220]	Photometric sensors to capture illuminance
	Daylight Glare Probability (DGP3)	Konstantzos, et al. [221]	HDR images taken by a digital camera
	Daylight Glare Index (DGI) or Cornell Equation metric	Hirning, et al. [222]	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. [177], Parsaee, et al. [186], Trivedi and Badarla [223], Heidari Matin and Eydgahi [224], Heidari Matin and Eydgahi [225], Al-Masrani and Al-Obaidi [226], Konstantoglou and Tsangrassoulis [227], Delzendeh, et al. [228], Ashouri, et al. [229], Miller, et al. [230], Fan, et al. [231], Hong, et al. [232]

Part 4. Some example studies of multi-objective optimization of façade's design: Buratti, et al. [233], Oral, et al. [234], Shahbazi, et al. [235], Lartigue, et al. [236], Goia, et al. [237], Ferrara, et al. [238], Zhai, et al. [239], Yi [240]

Chapitre 3: Human-centric lighting performance of shading panels in architecture: a benchmarking study with lab scale physical models under real skies

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Highlights

- Shading panels (SPs) were analyzed in terms of human-centric lighting factors.
- Impacts of SPs' color, reflectance, orientation, and openness have been explored.
- Blue-color SPs increase melanopic units and generate colder daylighting.
- Red-color SPs increase photopic units and produce warmer daylighting.
- Adaptive SPs must be developed to meet occupants' photobiological needs.

3.1 Résumé

Cette étude examine l'impact des panneaux d'ombrage (SP) sur les caractéristiques de l'éclairage naturel dans un modèle à l'échelle du laboratoire en termes de paramètres représentant les réponses biologiques potentielles de l'œil humain identifiées comme formation d'image (IF) et non formation d'image (NIF). Les réponses IF permettent la vision et les réponses NIF régulent les horloges internes du corps connues sous le nom d'horloges circadiennes. L'éclairage centré sur l'homme évalue les unités photopiques, représentant les réponses IF, et les unités mélanopiques représentant les réponses NIF, combinées avec la température de couleur corrélée (CCT) de la lumière afin de déterminer les effets biologiques potentiels. L'impact des SP sur ces paramètres de l'éclairage naturel n'a pas encore été étudié. Les recherches précédentes ont surtout étudié les impacts des panneaux sur le confort visuel et l'éblouissement liés aux réponses à l'IF. Cette recherche explore l'impact de la couleur, de la réflectance, de l'orientation et de l'ouverture des SP sur les unités photopiques et mélanopiques et la CCT de lumière naturelle à l'intérieur d'une maquette d'espace à l'échelle 1:50. Environ 40 prototypes de SP ont été évalués. Une installation expérimentale a été conçue dans des conditions d'éclairage naturel extérieur pour capturer des images à haute gamme dynamique (HDR) à l'intérieur du modèle. Les images HDR ont été post-traitées pour calculer et rendre la distribution des unités photopiques et mélanopiques, les ratios mélanopiques/photopiques (M/P) et les CCT dans le point de vue capturé dans le modèle. Les résultats révèlent le comportement de la couleur, de la réflectance, de l'orientation et de l'ouverture des SP en fonction de la modification des paramètres d'éclairage naturel liés aux réponses biologiques. Les panneaux bleus, en particulier, augmentent les unités mélanopiques et les CCT à la lumière du jour, alors que les panneaux rouges augmentent les unités photopiques et réduisent les CCT. Les résultats de la recherche ont été discutés en vue de fournir un canevas pour les futurs développements de panneaux visant à adapter l'éclairage naturel aux réponses des occupants en termes d'IF et de NIF.

3.2 Abstract

This study investigates shading panels' (SPs) impacts on daylighting features in a lab scale model in terms of parameters representing potential human eyes' biological responses identified as image forming (IF) and non-image forming (NIF). IF responses enable vision and NIF responses regulate internal body clocks known as circadian clocks. Human-centric lighting evaluates photopic units, representing IF responses, and melanopic units representing NIF responses, combined with correlated color temperature (CCT) of light for potential biological effects. SPs' impacts on such parameters of daylighting have not yet been studied. Previous research mostly studied panels' impacts on visual comfort and glare related to IF responses. This research explores the impact of SPs' color, reflectance, orientation, and openness on photopic and melanopic units and CCT of daylighting inside a 1:50 physical scale model of a space. Approximately 40 prototypes of SPs were evaluated. An experimental setup was designed under outdoor daylighting conditions to capture high dynamic range (HDR) images inside the model. HDR images were post processed to calculate and render the distribution of photopic and melanopic units, melanopic/photopic (M/P) ratios and CCTs in the captured viewpoint of the model. Results reveal the behavior of SPs' color, reflectance, orientation, and openness in modifying daylighting parameters related to biological responses. Bluish panels, in particular, increase daylighting melanopic units and CCTs whereas reddish panels increase photopic units and reduce CCTs. The research results were discussed to provide an outline for future developments of panels to adapt daylighting to occupants' IF and NIF responses.

3.3 Introduction

3.3.1 Human-centric lighting and photobiological units

The human-centric lighting approach, also known as integrative, healthy, biodynamic, or circadian lighting [12, 122], aims at adapting buildings' lighting to individuals' physical and mental health related to image forming (IF) and non-image forming (NIF) responses. IF or visual responses refer to the biological process among human eye's classical photoreceptors', rods and cones, and the brain after light reaching the retina which result in vision and image formation [13, 58]. IF effects have widely been studied in lighting science, especially in terms of human visual performance and energy issues [12, 13, 50]. More recently, biological studies revealed the new human eye's photoreceptors, known as intrinsically photosensitive retinal ganglion cells (ipRGCs). NIF responses refer to the impacts of light on the human eyes' ipRGCs regulating internal body clocks (or circadian clocks), alertness, performance, and mood [94, 123, 241]. Circadian clocks are entrained nearly every 24 hours and synchronized by local photoperiods, i.e., seasonal day/night cycles [43, 123, 242]. Daylight and photoperiods, thus, play a key role in stimulating NIF responses. The Commission internationale de l'éclairage (CIE) recommends to prioritize daylighting as the main source of lighting in the space because of extensive health and wellbeing benefits [12, 125] revealed by photobiological studies. Photobiology is the study of impacts of light on living organisms [49]. Photobiological studies claim that an improper lighting for NIF requirements could cause several wellbeing issues such as desynchronized circadian clocks, sleep problems, seasonal affective disorder (SAD), cardiovascular disease and low energy [78, 79, 84]. Therefore, human-centric lighting calls for special attention to occupants' photobiological requirements for different lighting qualities for various activities in the building.

Human-centric lighting evaluates the lighting quality of a space in terms of photopic and melanopic units and color temperature as the major factors affecting individuals' IF and NIF responses. Recent studies revealed that IF and NIF effects have different sensitivity to the intensity, spectrum, timing, and duration of light as well as the lighting exposure history of individuals [65, 119, 124, 241]. In terms of the effective spectrum, the human IF responses' spectral power is represented by the photopic curve peaked at 555 nm (see Figure 3. 2 in the following section) [66, 68]. The NIF responses' spectral power is presented by the melanopic curve peaked at 485 nm (see Figure 3. 2 in the following section) [66, 68]. The CIE recently proposed photopic and melanopic units representing potential human IF and NIF responses to the incident light at eyes [12, 90, 125]. Few studies have recently been published evaluating building lighting design in terms of photopic and melanopic units, such as Jung [76], Potočnik and Košir [243]. Photopic and melanopic intensities of a light source or a scene can be different because of diverse photopic and melanopic efficiencies. For example, 200 photopic lux of an incandescent light produces 108 equivalent melanopic (EM) lux [93]. The ratio of melanopic/photopic (M/P) units is proposed to consider both IF and NIF response curves in the evaluation of a light source or a scene [93, 127]. Table 1. 1 provides M/P ratios of some typical light sources as provided by Berman and Clear [127], Berman and Clear [244]. When the M/P ratio is 1 (M/P=1), it means the light source or the scene has almost equal melanopic and photopic intensities generating equal NIF and IF effects. When the M/P ratio is higher than 1 (M/P>1), for example 1.20 for a typical D-55 daylighting (Table 1.1), it means the melanopic intensity of the light or the scene is higher, about 20%, than the photopic intensity which potentially contributes to higher NIF responses than IF. For different lighting conditions, the higher M/P ratio means the higher melanopic intensity. On the contrary, when the M/P ratio is less than 1 (M/P<1), for example 0.64 for an incandescent lamp (Table 1.1), it means the photopic intensity of the light or the scene is higher, about 36%, than the melanopic intensity which potentially contribute to higher IF responses than NIF. For different lighting conditions, the lower M/P ratio means the higher photopic intensity. In addition to the M/P ratio, the correlated color temperature (CCT) of light is also considered in photobiological and human-centric lighting studies. Warm lights (CCT < ~3000 K) generally contribute to higher photopic units (M/P<1) whereas cool lights (CCT > ~5000 K) mostly contribute to higher melanopic units (M/P>1). It can also compare different warm or cool light sources' photopic and melanopic intensities. For example, in Table 1.1, a typical fluorescent with 3450 K color temperature (M/P=0.56) has a higher photopic intensity than a typical incandescent lamp with 2810 k color temperature (M/P=0.64). Similarly, a D75 daylighting with 7500 K color temperature has a higher melanopic intensity (M/P=1.43) than a D55 daylighting with 5500 K color temperature (M/P=1.2). Table 1.1 provides M/P ratios for different color temperatures of some light sources. In terms of the timing and duration of exposure, the CIE stated that a proper lighting quality must be provided at the right time of the day for different tasks and activities in buildings to ensure occupants' health [12, 125]. The hourly photobiological lighting requirements are different for various activities and building uses. For example, for daytime activities in offices, most recent studies recommend cool lighting with high melanopic intensities in the morning which follows by warm lighting with low melanopic intensities in the afternoon and evening [245]. Therefore, human centric lighting focuses on providing proper photopic and melanopic units and color temperature of lighting at the proper time of the day to meet building occupants' photobiological needs.

Table 3. 1. M/P ratios and color temperatures of some typical light sources provided by Berman and Clear [127], Berman and Clear [244]

Source	CCT	M/P ratio
High-pressure mercury	2970	0.29
Fluorescent	3540	0.56
Incandescent lamp	2810	0.64
Daylight fluorescent	5140	1.07
Fluorescent (6500 K)	6380	1.18
D55 (daylight 5500 K)	5500	1.20
D65 (daylight 6500 K)	6510	1.33
D75 (daylight 7500 K)	7500	1.43

3.3.2 Importance of the research

This paper presents a benchmarking experimental study aimed at exploring shading panels' (SPs) impacts on human-centric parameters of daylighting, i.e., photopic and melanopic units and color temperature, in a lab scale model of a space. Studying SPs' human-centric performance can foster healthy daylit spaces' developments responding to IF and NIF requirements. Panels and louvers are often utilized in different buildings, as in Figure 3.1, to control visual comfort and glare [226, 227, 246, 247] corresponding to IF responses [119, 122] as well as reducing heating and cooling loads corresponding to energy issues [226, 227, 246]. More recently, photobiological impacts of the window's configuration [248], glazing color [243, 249], and indoor surface colors and reflectance [141, 250, 251] have also been explored. Such studies have shown that the window-to-wall ratio (WWR), the color of glazing and the reflectance of the interior surfaces could modify the intensity and distribution of IF and NIF factors in the space. These studies have considered different lighting conditions from real and simulated overcast and clear skies to cool and warm white indoor artificial lighting. The studies also evaluated lighting performance inside a real building, lab scale, or simulated model. The studies provide some recommendations about spaces' configurations for occupants' IF and NIF requirements for different activities. For example, Acosta, et al. [248] concludes that the indoor surface reflectance can considerably affect circadian entrainment and lighting spectral distributions. Cai, et al. [141], Yao, et al. [250], Dai, et al. [251] have worked on proposing a metric and equation which could represent the relationship between circadian stimulus, photopic illuminance, room surface reflectance and WWR. Panels' impacts on daylighting features related to NIF responses have not yet been studied [119, 245].

This research investigates the impact of SPs' configurations on daylighting features related to occupants' IF and NIF responses. The objectives and hypotheses of the research were discussed in detail in the following section regarding the human-centric lighting approach and the existing knowledge gap. The per-pixel image-based measurement methodology is explained in terms of the experimental setup to capture human-centric parameters of light in a lab scale physical model under actual daylighting conditions in Quebec, QC, Canada (Lat. 46° 48´ N, Lon. 71° 12´ W). The design configuration is explained in terms of different colors, reflectance, orientations, and openness considered to build approximately 40 models of SPs. The discussion elaborates on SPs' human-centric performance through identifying the impacts on the intensity and distribution of photopic and melanopic units and color temperature in the space. The conclusion outlines the main issues related to photobiological performance of SPs for future developments of adaptive strategies to meet occupants' IF and NIF needs. The research outcomes could apply to optimize panels to control photopic and melanopic units and color temperature of daylighting during the day in order to provide occupants with a proper daylighting quality at a proper time responding to their IF and NIF needs. Research results can be transposed into rule-of-thumbs for designing adaptive SPs for healthy daylit spaces, potentially applicable for architects and lighting designers.

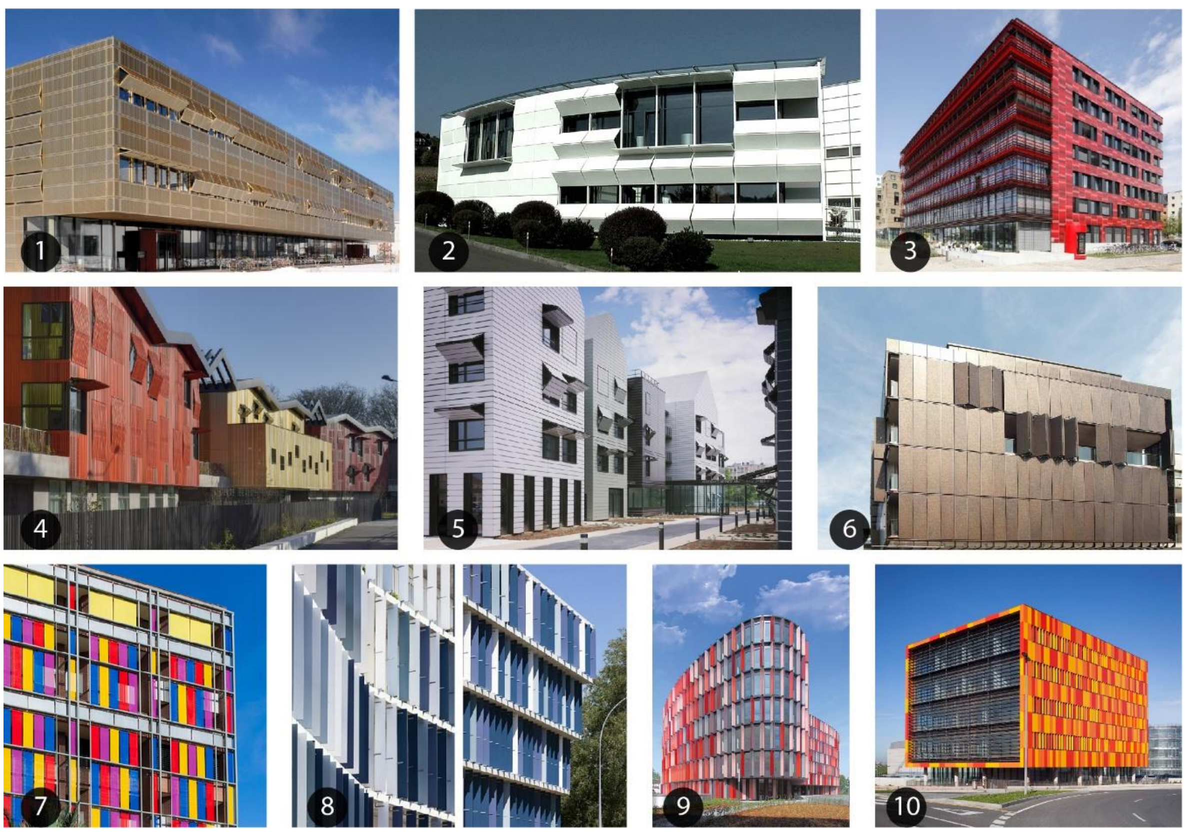


Figure 3. 1. Examples of different shading panels utilized for buildings (the courtesy of photos are given in Appendix 3.A)

3.3.3 Objectives and hypotheses of the research

The main objective of this research is to study the human-centric performance of SPs' configurations, including color, reflectance, orientation, and openness, in terms of daylighting photopic and melanopic units and color temperature representing potential IF and NIF responses. As can be seen in Figure 3.1, shading devices have been built in different colors, reflectance, and orientations. This research hypothesizes that SPs' color, reflectance, orientation, and openness could modify the daylighting spectrum resulting in the modification of photopic and melanopic units inside buildings. The hypothesis is based on the fact that surface characteristics in terms of color and reflectance could affect the spectral power of incident light as well as the daylighting distribution in the space [13, 187]. For example, a typical clear-sky sunlight spectral power is recognized as D55 illustrated in Figure 3.2-a [13, 64]. The spectral powers of bluish, yellowish, and reddish colors, as some examples of test color samples (TCS), are also reported as Figure 3.2-b [252]. Changing the surface's finishing color to blue, yellow, or red, for instance, can hypothetically modify daylighting spectral resulting in higher or lower photopic and melanopic units related to IF and NIF responses. The research also hypothesizes that the SPs' orientation and openness can modify the penetration and distribution of daylighting in the space affecting photopic and melanopic units and CCTs. Overall, the research hypothesizes that such SPs' design variables could change the spectral composition and distribution of daylighting admitted to interiors and modify the relative power of wavelengths related to photopic and melanopic units and CCT.

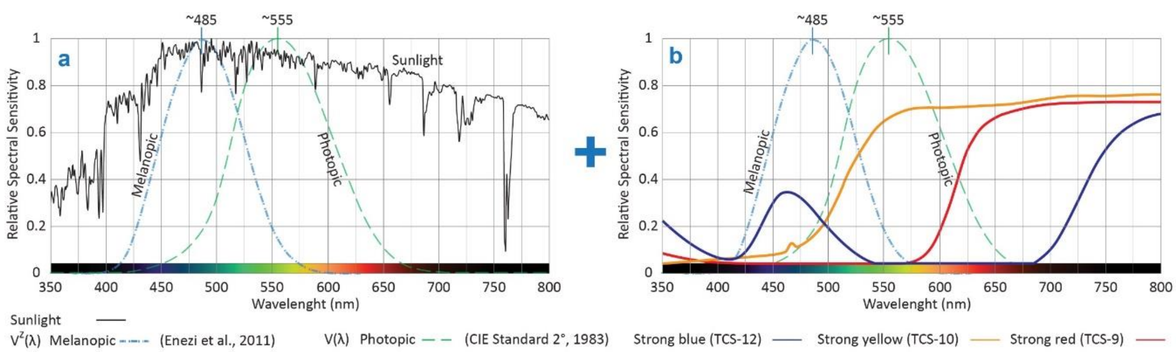


Figure 3. 2. (a) spectral power distributions of the D55 CIE daylighting illuminant (retrieved from DiLaura, et al. [13], ASTM G173-03 [64]), photopic responses (retrieved from DiLaura, et al. [13]) and melanopic responses (retrieved from Enezi, et al. [66], Amundadottir, et al. [68]), (b) spectral power distributions of strong blue (TCS-12). strong yellow (TCS-10) and strong red (TCS-9) colors (retrieved from Wavform Lighting [252])

3.4 Methodology

3.4.1 Experimental setup

A model and an experimental setup were developed at a 1:50 scale to align with typical practices of early stages of design and architectural explorations. Physical models are recognized as a soft technology which can be built at all stages of architectural and daylighting design processes, and shared to different building professionals [187]. Physical modeling of spaces and buildings at different scales from 1:500 to 1:10 are commonly used in architectural practices and educations around the world [187, 253]. Physical models at 1:100 to 1:50 scales are mostly used to evaluate daylighting penetration, distribution and intensity levels as well as the efficiency of solar protections [187, 253]. In this study, a three-story high scale model of a building was built, made of wood for the floor and ceiling, white-color paper walls and a clear acrylic opening, as can be seen in Figure 3.3-a. The dimension and ratio of the scaled building model were verified based on past studies from Poirier, et al. [138], Jafarian, et al. [140]. All edges and joints were carefully sealed to prevent any light leakage, as recommended by Ruck, et al. [187], Baker, et al. [253]. Surfaces characteristics are provided in Table 2. This three-story high scale model, which does not have any panel, was considered as the reference model, Case-0. The model has been directed towards the south in the direction of sunlight at 10:30 to 15:00, on April 30, 2019, in Quebec, QC, CA. The outdoor daylighting conditions are described in the following section.

The panels were installed in front of the reference model in order to evaluate their impacts on daylighting inside the model. All panels were built and prepared before the experiment to save time. Two persons were responsible to proceed to panels' configuration changes during parametric studies to optimize the number of captured images with the camera. It took about one minute to change the panels of one configuration setup. As illustrated in Figure 3.3-b, a network of Raspberry Pi microcomputers with camera modules were used to capture low dynamic range (LDR) images from side and back views in the model. The server, consisting of a portable computer, contained a python script to remotely accesses all Pi's through the secure shell (SSH) protocol. All Pi's contained a Python script to run the camera module, capture and store multiple LDR images with different exposure values (EV), ranging from nearly -3 EV (very dark) to +3 EV (very bright). The python script runs all Pi's cameras simultaneously on the server, taking about 40 seconds to capture all LDR images. Transporting the model to outdoors began from 8:30 in the morning. Setting the model, preparing the panels, and running few preliminary tests took about 2 hours. The measurements, thus, started from 10:30 to around 13:30.

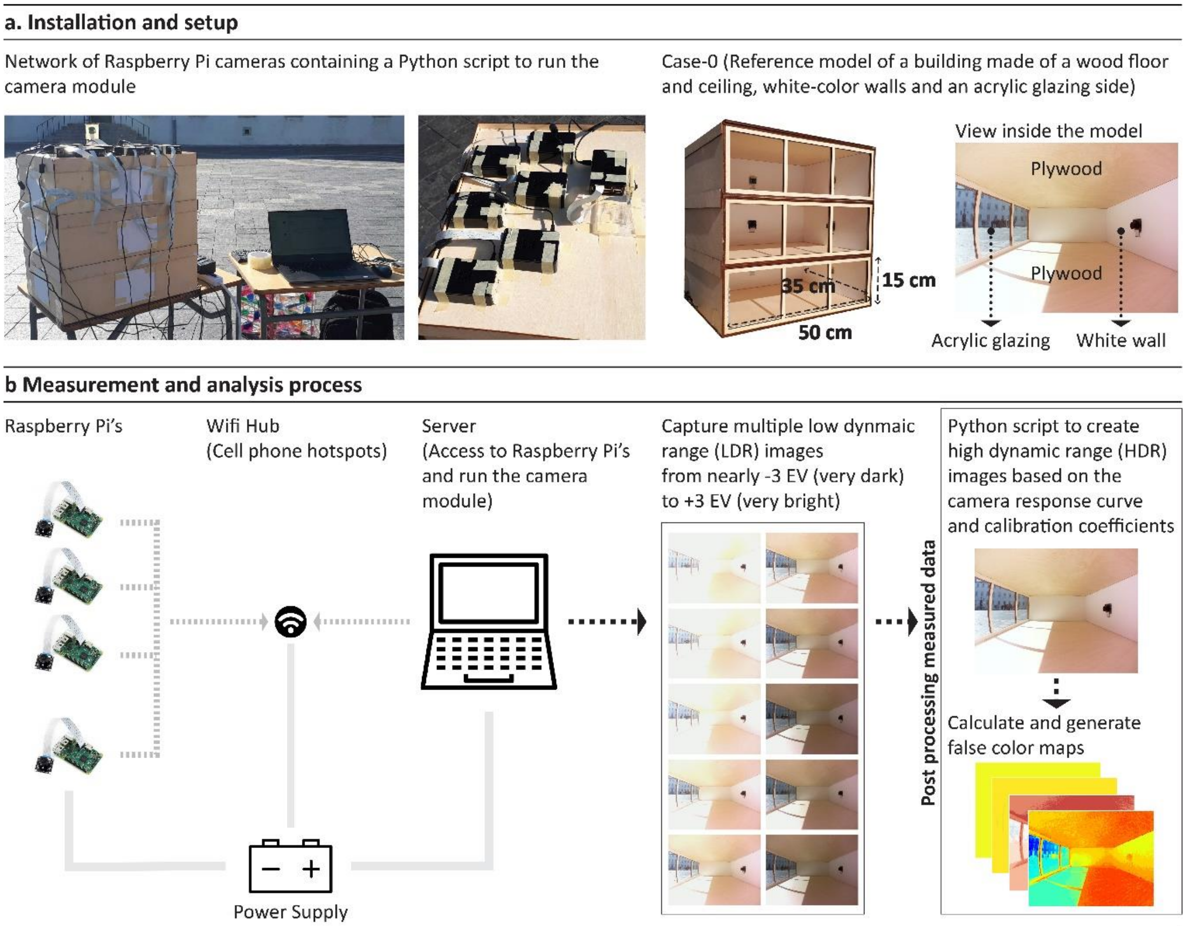


Figure 3. 3. The research experimental setup, measurement, and analysis process to evaluate different shading panels

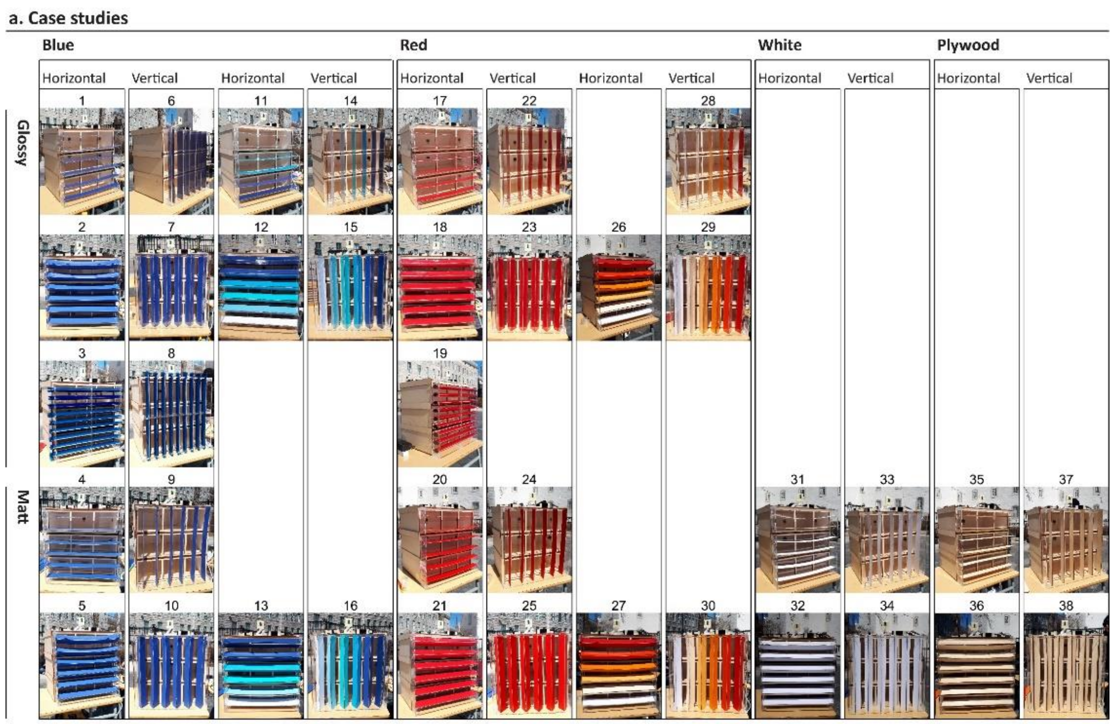
3.4.2 Models and design variables

The experimental setup enables capturing lighting performance of scaled SPs' models under an actual outdoor daylighting condition. The panels were built with plywood, color carton papers and plastic covers to be an affordable exploratory study. Approximately 40 models of SPs were produced at the scale of 1:50 by changing the color, reflectance, orientation and openness of panels, as shown in Figure 3.4-a including matt and glossy blue (Figure 3.4-a, cases 1-16), matt and glossy red (Figure 3.4-a, cases 17-30), matt cool white (Figure 3.4-a, cases 31-34) and plywood Figure 3.4-a, cases 35-48). The colors were chosen based on TCS spectrums provided by Wavform Lighting [252] to cover different colors spectral enriched in various wavelengths from longwaves to shortwaves. Two sets of panels were built with a blue tone (cases 11-16) and red tone (cases 26, 27, 29 and 30) colors as an architectural exploration similar to the example buildings provided in Figure 1. The typical specularity value (SV), lighting reflectance value (LRV) and visible transmittance (VT) of materials used in the models are presented Table 3.2 determined by [254-256]. The panels' daylighting performance was also assessed in terms of horizontal and vertical orientations. The panels were assembled in a large openness, about 90% view to outside, and a small openness, about 20% view, in order to explore the impact of panels' openness on daylighting performance. Such openness degrees were chosen to identify the panels' impacts when they are designed to cover the opening regarding the research hypothesis and existing buildings as the examples in Figure 3.1. The panels' openness degree could, generally, be changed from 0 to 100% under different dynamic behaviors. However, different variations of openness were not applicable in this study due to the scale of the model. Overall, eight scenarios were considered to evaluate the daylighting behavior of SPs' design variables, as presented in Figure 3.4-b and explained in the following.

- **Scenario 1:** the behaviour of different panels' colors with matt reflectance, horizontal orientation, large openness
- **Scenario 2:** the behaviour of different panels' colors with matt reflectance, horizontal orientation, and small openness
- **Scenario 3:** the behaviour of different panels' colors with glossy reflectance, horizontal orientation, and large openness
- **Scenario 4:** the behaviour of different panels' colors with glossy reflectance, horizontal orientation, and small openness
- **Scenario 5:** the behaviour of different panels' colors with matt reflectance, vertical orientation, and large openness
- **Scenario 6:** the behaviour of different panels' colors with matt reflectance, vertical orientation, and small openness
- **Scenario 7:** the behaviour of different panels' colors with glossy reflectance, vertical orientation, and large openness
- **Scenario 8:** the behaviour of different panels' colors with glossy reflectance, vertical orientation, and small openness

Table 3. 2. Material characteristics of typical materials used in the model determined by Integrated Environmental Solutions [254], Solemma [255], Magali, et al. [256]

Material	**Specularity value (SV, %)**	**Lighting reflectance value (LRV, %)**	**Visual transmittance (VT, %)**
Plywood	0	25- 35	
Clear acrylic		5-10	80-90
White color - Matt	0	70-80	
Strong blue color - matt	0	5-10	
Strong blue color - glossy	5-10	35-45	
Light blue color - Matt	0	65-75	
Light blue color - Glossy	5-10	75-80	
Strong red color - Matt	0	10-15	
Strong red color - Glossy	5-10	55-65	
Orange color - Matt	0	35-45	
Orange color - Glossy	5-10	75-85	
Canson paper – white		80-85	
Canson paper – strong blue		5-20	
Canson paper – light blue		70-75	
Canson paper – strong red		15-20	
Canson paper – orange		25-45	



b. Experiment scenarios

	Color scheme	Reflectance		Orientation		Openness	
	Blue, Red, White, Wood	Matt	Glossy	Horizontal	Vertical	Large (~90%)	Small (~20%)
Scenario 1	variable	●		●		●	
Scenario 2	variable	●		●			●
Scenario 3	variable		●	●		●	
Scenario 4	variable		●	●			●
Scenario 5	variable	●			●	●	
Scenario 6	variable	●			●		●
Scenario 7	variable		●		●	●	
Scenario 8	variable		●		●		●

Figure 3. 4. (a) The case studies of shading panels at the scale of 1:50, (b) different experiment scenarios to evaluate the daylighting behaviour of shading panels' design variables

3.4.3 Photobiological measurements and analysis

This research has employed high dynamic range (HDR) imagery and post-processing techniques which enable graphical presentations of photopic and melanopic units' and CCTs' distributions of light within the camera field of view. Such graphical representations contribute to the architectural perception and understanding of daylighting performance in the space [257]. Wide-angle lenses, with 170° field of view, mounted on Pi cameras were installed in the middle space offering a field of view similar to human eyes. The bottom and top spaces were equipped with 35 mm camera lenses. HDR images were generated and calibrated through merging LDR images from low to high EVs (over- and under-saturated images were discarded) as recommended by Debevec and Malik [258], Jakubiec, et al. [259], Pierson, et al. [260]. As shown in Figure 3. 5, the HDR imagery of fisheye cameras were calibrated for XYZ (CIE Tristimulus channels) and RBG (Red-Green-Blue) channels based on Jung [76], Jung and Inanici [216] through measurements under direct sun lighting, overcast daylighting sky, and artificial diffuse overcast skies with cool, moderate and warm color temperatures. The captured HDR images were numerically processed and analyzed in terms of photopic and melanopic units, M/P ratio, CCT, and distribution density function of photopic, melanopic, M/P ratios and CCTs. The photopic, melanopic, CCT data is derived from RGB pixel values of the HDR images based on the method developed by Jung [76], Jung and Inanici [216]. Photopic false color maps were plotted in cd/m2 in a logarithmic scale with a threshold of 3000 cd/m2 to indicate glare probabilities [213, 261]. Melanopic false colors were plotted in EMcd/m2 in a logarithmic scale [76, 216].

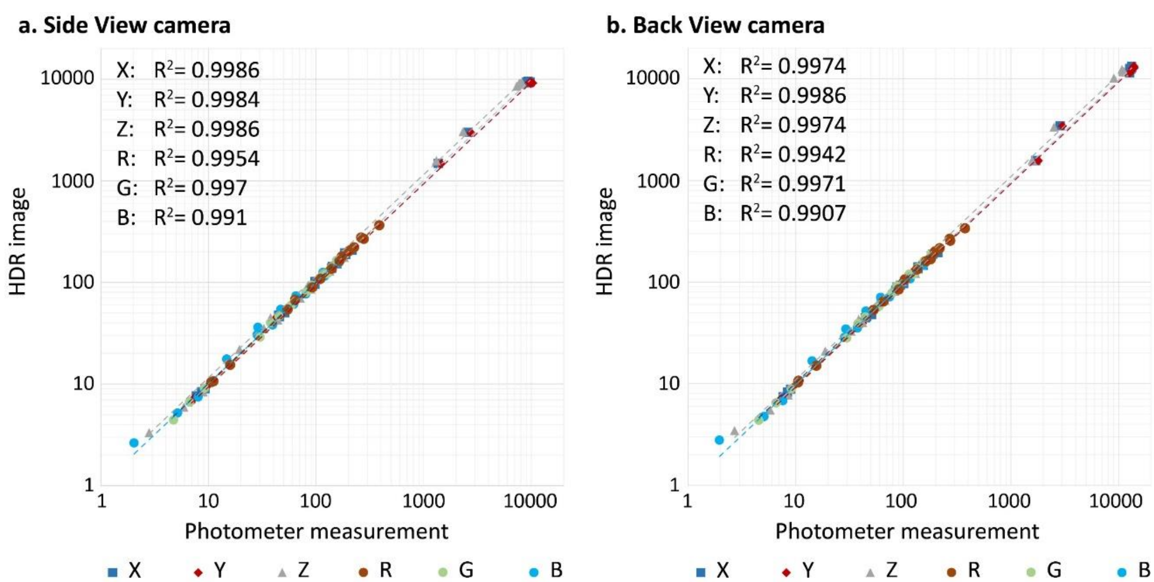


Figure 3. 5. Raspberry Pi fisheye cameras' calibration for XYZ and RBG channels

3.4.4 Outdoor context

The experiment has been conducted from 10:30 to 13:30 on April 30, 2019, under a clear sky with no cloud cover (cloud cover = 0) in Quebec, as shown in Figure 3. 6. The outdoor lighting conditions were measured for the vertical surface towards the same direction around every 30 minutes during the experiment by using a photometer device: Konica CL-200A Chroma Meter. The photometers measured the photopic lux and color temperature of the exterior scene in the same direction of the scale model towards the south. Figure 3. 6 shows the recorded outdoor lighting conditions during the experiment performed about three hours around the noon. As can be seen in Figure 3. 6, daylighting illuminance has been relatively constant around 85000 lux and 5500 K. As the cloud cover, daylighting intensity and CCT were stable, the solar geometry had negligible effect on the experiment (Figure 3. 6).

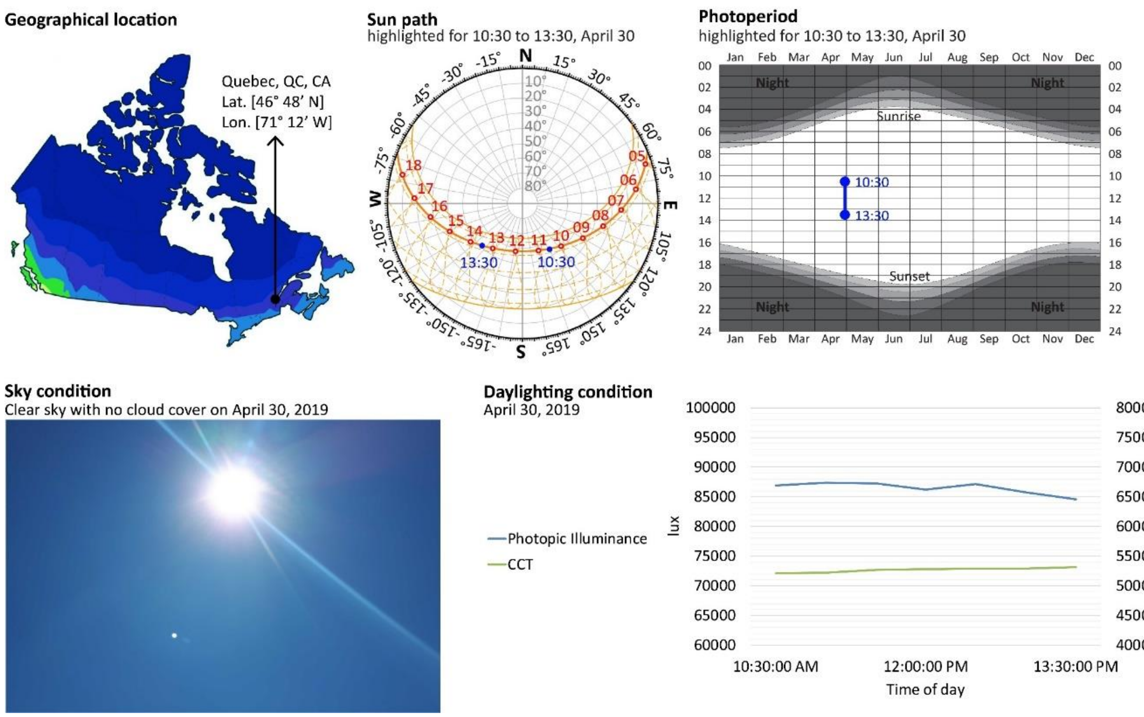


Figure 3. 6. Geographical location and outdoor solar conditions of the study during the experiment

3.5 Results

The results are provided with regards to the studied SPs' design variables impacts, including color, reflectance, orientation, and openness, on daylighting human-centric features as the following subsections. Photopic and melanopic luminance false color maps are calculated for all captured scenes showing the spatial distributions of photopic and melanopic luminance intensities of light within the space. The M/P ratio is calculated in a false color format providing a graphical representation of how and where melanopic or photopic unit is dominated in the captured scene. In M/P ratio false color maps, the blue tone represents high M/P ratios which means melanopic luminance is dominated (melanopic luminance > photopic luminance). In contrast, the red tone represents low M/P ratios which means photopic luminance is dominated (melanopic luminance < photopic luminance). The white tone means melanopic luminance is almost equal to the corresponding photopic luminance (melanopic luminance = photopic luminance). Violin plots of M/P ratios of all cases are plotted in Figure 3. 7 to identify the frequency and accumulation of melanopic or photopic unit domination. The results are explained for the middle space of the model because the wide-angle camera lenses offer a field of view similar to human eyes. The calculated false color maps of all models from the second-floor side view viewpoint are provided in Appendix 3.B.

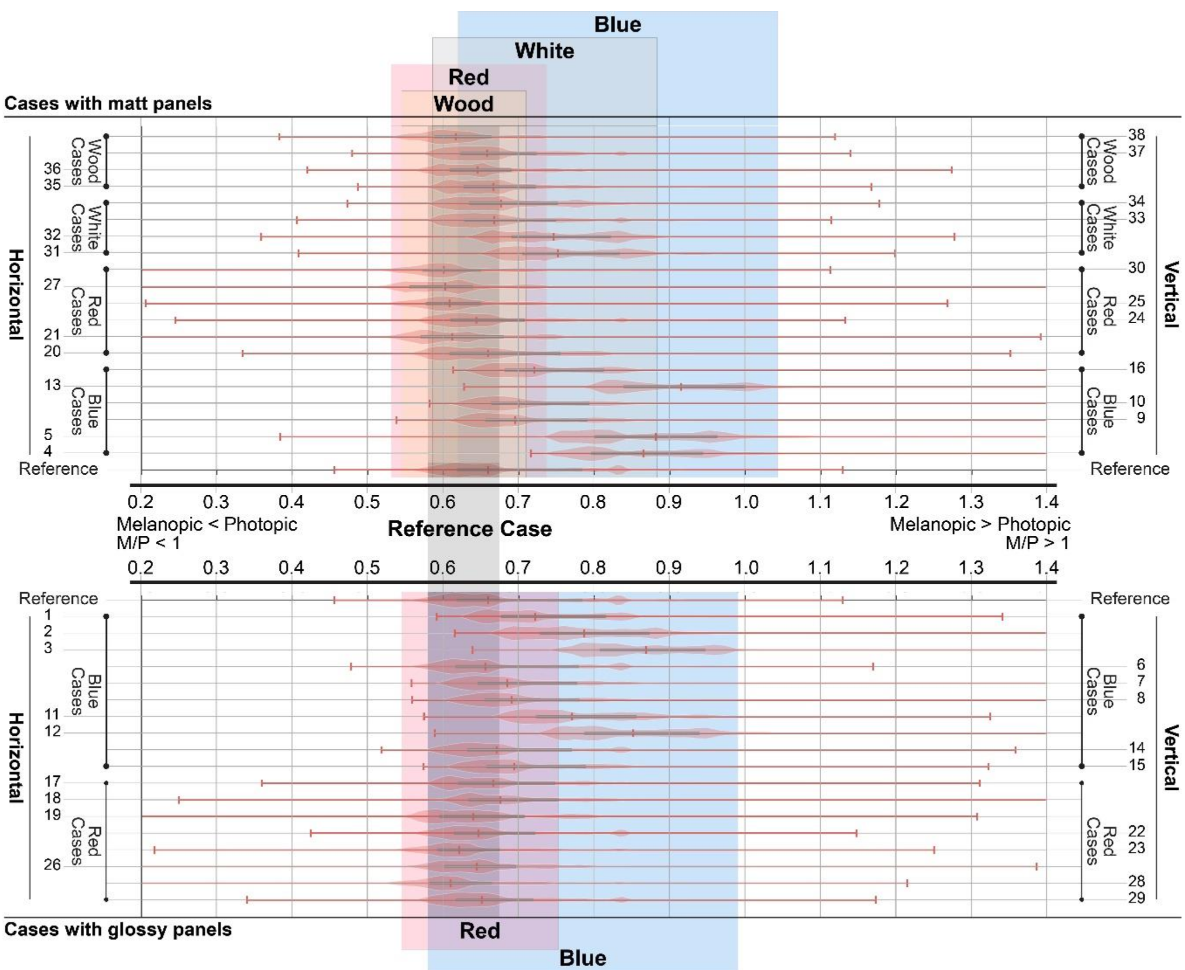


Figure 3. 7. The frequency and accumulation of melanopic/photopic (M/P) luminance ratios within the captured scenes from the side view for all studied panels

3.5.1 Daylighting features of the reference model

Daylighting features of the reference model, case-0, are explained to realize the SPs' impact on human-centric parameters. The false color maps of the reference model, case-0, are illustrated in Figure 3. 8 indicating photopic units are dominated when no panel is applied. As can be seen, M/P ratios are mostly accumulated between 0.6 and 0.7 meaning photopic luminance is higher than melanopic luminance. The intensity of photopic and melanopic exceeds 3000 cd/m^2 and EMcd/m^2, respectively, inside the space because of the direct sun light. The M/P ratios of the reference are mostly accumulated between 0.6 and 0.7, as can be seen in Figure 3. 8. The color temperature of daylighting is changed from around 5000 K near the glazing to 2500 K near the back surface at the end of the space. Note that the outdoor lighting is higher than 80000 lux and around 5000 K on the vertical surface during the experiment (see Figure 3. 6).

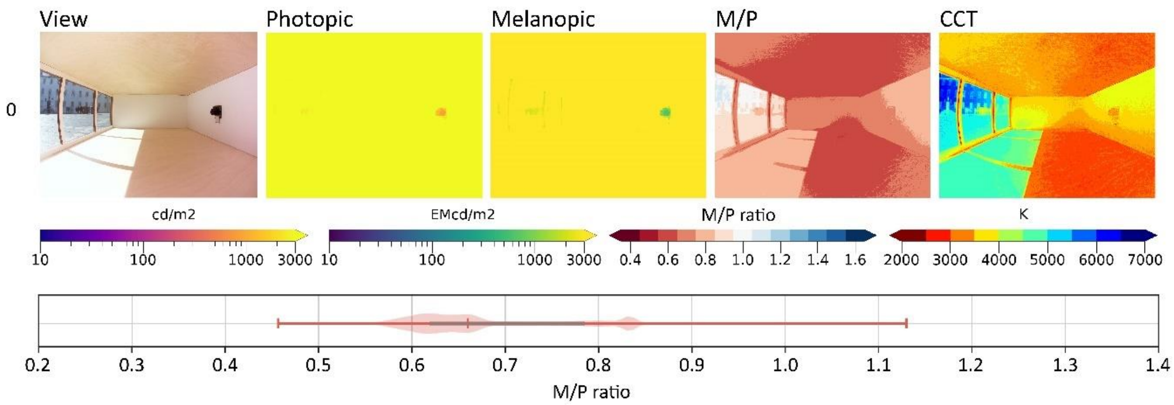


Figure 3. 8. Daylighting features in the reference, case-0.

3.5.2 Human-centric performance of panels' color

The results show blueish SPs can increase the intensity and distribution of melanopic luminance in the space whereas reddish panels contribute to the photopic luminance intensity and distribution. The false color maps of blue-color SPs, cases 1-16, show that melanopic luminance is considerably magnified in the scene compared to the reference case. As noticeable in such cases, a bluish color is appeared in the field of view. Considering Figure 3. 7, M/P ratios are distributed towards higher melanopic units. The M/P ratio frequency of blue-color panels is accumulated from nearly 0.6 to 1.05 indicating up to 30% increase compared to the corresponding range for the reference which is around 0.6 to 0.7. The significant increase of melanopic luminance is highly noticeable in cases 2-6 and 13-15 as some of them illustrated in Figure 3. 9. The melanopic domination is also significant in the area close to the panels, near the glazing. Moreover, the bluish panels increase the daylighting color temperature inside the space. For example, Figure 3. 9 shows the CCT is increased to 4000 K and above all over the scene in cases 2-6 and 13-15 indicating considerable differences compared to the CCT distribution in the reference. The CCT is maximized near the glazing, close to the panels, reaching above 7000 K in some cases such as Figure 3. 9.

The cool whitish SPs have similar behavior with slighter impacts on human-centric features compared to the bluish SPs. The white-color panels, cases 31-34, slightly increased melanopic units compared to the reference case. M/P ratio distributions of the white-color SPs are mostly accumulated from 0.6 to slightly above 0.85 accounted to 15% increase compared to the reference (see Figure 3. 7). As can be seen in white-color cases in Figure 3. 9, a whitish color is appeared in the viewpoint. The white-color panels also affected the CCT in the scene fluctuated from around 5000 K near the opening to 3500 K near the back surface of the space.

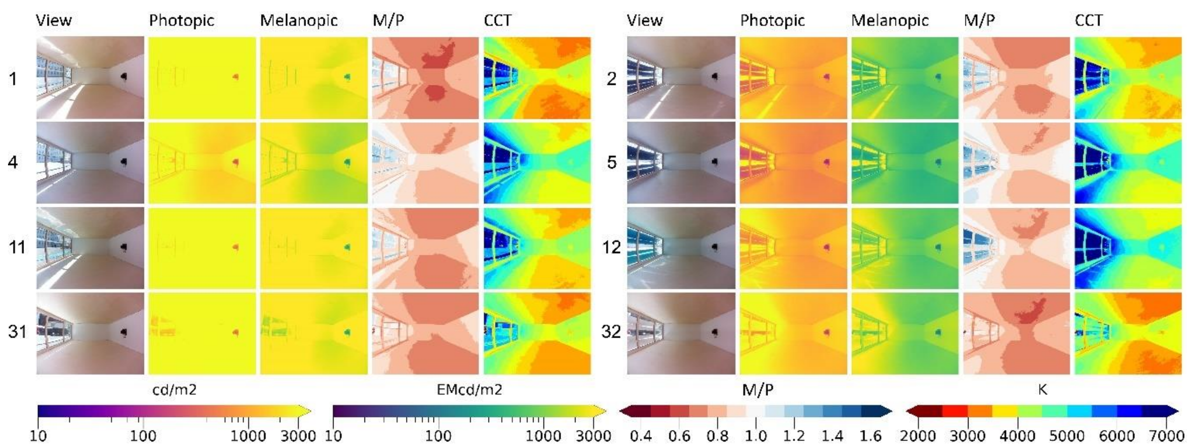


Figure 3. 9. Human-centric performance of some of the blue- and white-color shading panels

In contrast to bluish and whitish panels, the red-color SPs affect photopic units of daylighting and magnify the low M/P ratios within the scene compared to the reference. The false color maps of the reddish panels, cases 19-34, show that M/P ratios are significantly decreased within the scene, representing higher photopic luminances. Considering Figure 3. 7, the reddish SPs' M/P ratios are mostly accumulated between around 0.55 to 0.75. The color temperature of daylighting is dropped to under 2500 K in cases such as 20 and 21 (Figure 3. 10). A reddish color is observed in the field of view. Considering the floor and ceiling surfaces, the maximum CCT is mostly distributed near the opening whereas the minimum CCT is recorded near the back surface of the scene.

Wood panels, cases 31-34, had slighter impacts on photopic units compared to the red-color panels. As some examples are given in Figure 3. 10, the false color maps of cases 31 and 32 show that the M/P ratios distribution is changed towards lower photopic luminances. The frequency of M/P ratios is distributed within about 0.55 to slightly above 0.7 which is close to the corresponding range of the reference (Figure 3. 7). The daylighting color temperature pattern is decreased in the scene distributing from about 4000 K near the opening to around 3000 K near the back wall. A slight yellowish lighting is observable in the space.

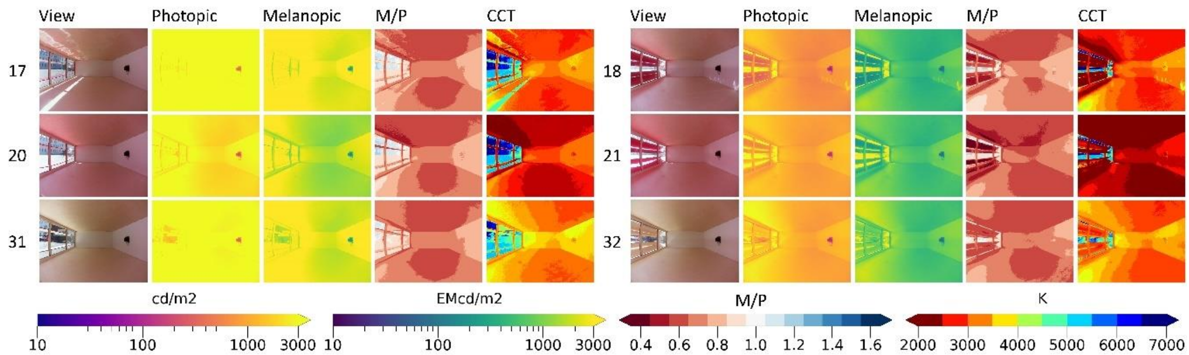


Figure 3. 10. Human-centric performance of some of the red-color and wood shading panels

3.5.3 Human-centric performance of panels' reflectance

The reflectance of the panels affects the magnitude of color's impacts on daylighting human-centric features all over the space. The reflectance of panels is examined as an independent variable by using the identical form, color, and orientation for glossy and matt surfaces. Considering as an independent variable, the matt panels' human-centric impacts are magnified compared to the glossy panels with same color, orientation, and form. As some examples are given in Figure 3. 11, the impacts of matt bluish and reddish SPs are intensified compared with glossy SPs with similar color and orientation. In Figure 3. 11, the matt panels have more impacts on the intensity and distribution of photopic and melanopic units, M/P ratios and CCT in the scene compared to glossy panels. As can be seen in violin plots in Figure 3. 11, the M/P ratios of matt bluish cases are mostly accumulated between around 0.75 to 1.05 whereas the corresponding range for the glossy bluish panels are around 0.65 to 0.95. For the reddish panels, the M/P ratios of matt panels are distributed from nearly 0.55 to above 0.65 whereas the distribution range for glossy panels is between 0.6 to under 0.7. Moreover, the CCT is intensified in the scene with the matt panels compared to the glossy cases, e.g., the matt blue panels in case 4 generated a colder light, around 5000 K, on the back wall compared to the glossy blue panels in case

1 projecting a 4000 K -light on the wall. Likewise, the matt red panels in case 21 produce a warmer light, around 2500 K, than the glossy red panels generating a 3500 K light on the back wall.

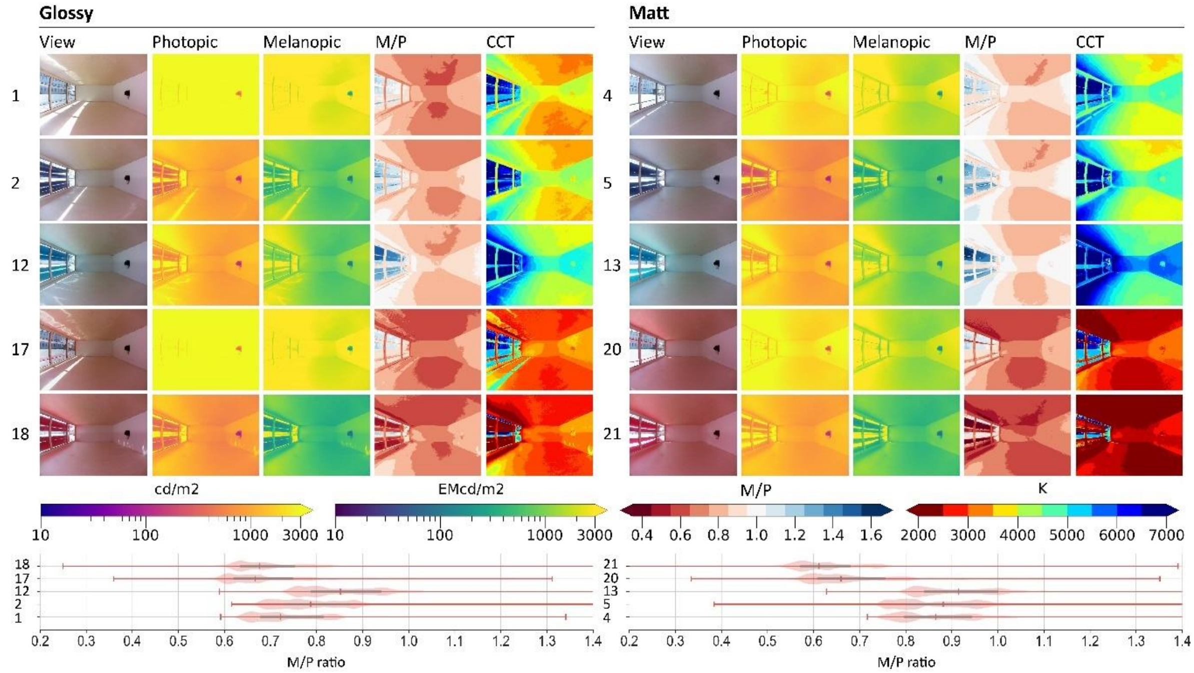


Figure 3. 11. Human-centric performance of panels' reflectance: glossy vs. matt

3.5.4 Human-centric performance of panels' orientation and openness

The horizontal panels can significantly obstruct the direct sunlight penetration into the interior and modify daylighting features for the South-facing window compared to vertical panels (Figure 3. 12). The size of openness between panels is intensified such behaviors as can be seen in Figure 3. 12, e.g. cases with a large openness, 1, 6, 20 and 24, compared to cases with a small openness 2, 7, 21 and 25. As the experimentations performed around the noon for the south direction, the horizontal panels significantly affect the intensity and distribution of photopic and melanopic units, M/P ratio and CCT all over the scene compared to the reference (see Figure 3. 12 and Figure 3. 8). On the contrary, the vertical panels have no considerable impacts on photopic or melanopic units or CCT, especially in the area near the opening. By reducing the openness between panels, the vertical SPs have more impacts on the daylighting penetration and human-centric features in the space. The impacts of vertical panels are yet lower than the horizontal panels with similar configurations and openness. Decreasing the openness between panels also reduces the risk of glare in the space, as can be seen in Figure 3. 12.

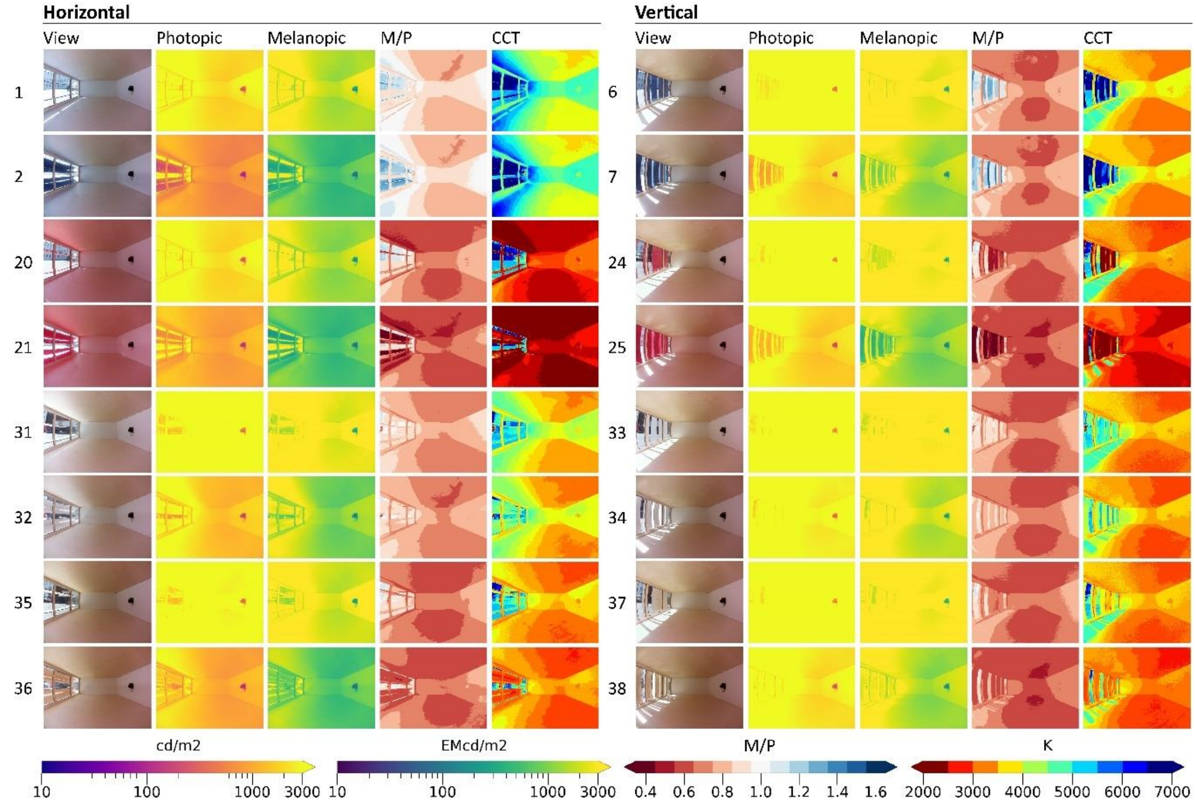


Figure 3. 12. Human-centric performance of panels' orientation and openness: Vertical vs. horizontal and small vs. large openness

3.6 Discussion

The benchmarking study reveals the impacts of SPs' design variables, including color, reflectance, orientation, and openness, on the human-centric lighting performance inside the space which could potentially modify occupants' photobiological responses. The panels' color has considerable impacts on photopic or melanopic units and color temperature of daylighting as fundamental factors representing IF and NIF responses. The color scheme is the determining factor for panels' behaviour to increase melanopic units and CCT or increase photopic and decrease CCT of daylight in the scene. Panels with blue-based and cold colors can increase melanopic units and color temperature in the space, up to 30% for the studied models. As shown by the research results, cool whitish SPs can also increase melanopic units and CCT of daylighting in the scene. The warm white color could presumably increase photopic units. Thus, bluish, and cool whitish panels could potentially affect NIF responses through increasing melanopic units and CCT. On the contrary, red-based and warm colors, such as yellowish wood and red panels, contribute to higher photopic units and lower color temperature and produce warmer daylighting resulting in potential IF modifications. Hence, the warm white color could presumably increase photopic units. Such behaviors confirm the research hypothesis that the panels' color modifies the daylighting spectrum content and affects melanopic and photopic units which can potentially result in different IF and NIF responses. Furthermore, the research results demonstrate that the panels' finishing reflectance affects the magnitude of color's impacts within the space. The impact of matt color SPs is intensified and magnified all over the scene compared to glossy finishing panels with similar color. Such behaviours generally attribute to the fact that glossy surfaces produce highlights in the range of white, whereas diffuse reflection is in the form of surface color. The glossy and matt behaviours confirm the research hypothesis in terms of panels' reflectance affect daylighting human-centric performance. The research was performed under clear sky and direct sun lighting. Color and reflectance behaviors must be further investigated for other colors and under different daylighting and sky conditions, e.g. overcast and clear skies with different CCTs.

Studying the panels' orientation for the south direction revealed that the horizontal SPs affect the human-centric features of daylighting all over the space, highly influential from near the opening to the end of the space near the back wall. The horizontal SPs could effectively block the direct sunlight reaching indoors. The vertical SPs, however, with small or large openness have negligible impacts on direct sunlight obstructions for the south façade. Decreasing the openness between panels can magnify the horizontal and vertical panels' impacts on daylighting features in the space. The vertical panels with a small openness have more impacts on the area near the back surface of the space compared to vertical panels with a larger openness. The small openness of horizontal and vertical panels also reduces the risk of glare in the scene. Further studied must be done to investigate the orientation impacts for other directions such west and east. Future research could also study different forms, sizes, and openness variations of panels.

This study calls for special attention to the human-centric performance of SPs and occupants' needs in different building uses. Having such considerable human-centric effects, panels' configurations must be adapted to different hourly IF and NIF requirements. Adaptation strategies and technologies must therefore be developed to adapt SPs' configurations, in terms of color, reflectance, orientation and openness, to occupants' photobiological needs. Adaptive SPs must be able to adjust daylighting human-centric features, including melanopic and photopic units and color temperature, in an hourly basis to meet occupants' IF and NIF needs for the specific activity in the space. For example, in Figure 3. 13, a lighting adaptation scenario has been developed for an office building in Cambridge Bay, Nunavut, Canada (Lat. 69° ° 1´ N, Lon. 105° 1´ W), proposing the pattern that lighting features must be changed hourly to respond to the occupants' IF and NIF needs throughout [245]. Considering the proposed scenario, SPs must modify daylighting to provide a high-intensity cold light in the morning following by a high-intensity white light around the noon and a low-intensity warm light in the late afternoon. SPs' color could be adjusted during the day to address the lighting scenario requirements as presented in the left column in Figure 3. 13. Adaptive SPs' must also respond appropriately to the local climate as local photoperiods drastically change by moving towards high-latitude sub-Arctic regions, near and above 50 °N. Adaptive panels could, hypothetically, be produced with different color sides and a controllable openness to be operated manually or automatically during the day to adapt the daylighting intensity and color temperature to occupants' IF and NIF needs. Such photobiologically responsive adaptive SPs could also be developed with insulated material to cover the opening when no daylighting is needed, hence, improving the building thermal performance in extreme cold climates[245]. Future research must develop such high-performance adaptive panels.

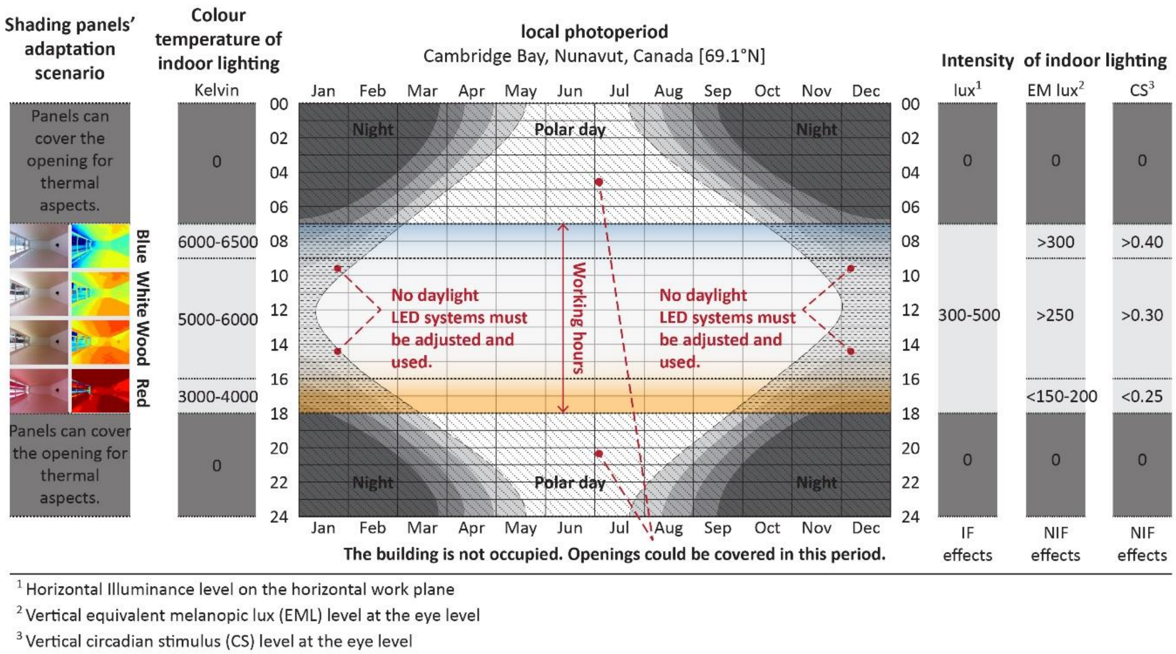


Figure 3. 13. Shading panel adaptation to the lighting scenario in an office building in Cambridge Bay, Nunavut, Canada based on Parsaee, et al. [245]

3.7 Conclusion

This benchmarking research showed the human-centric lighting performance of SPs' design variables, i.e., color, reflectance, orientation, and openness. The research findings can be concluded as the following.

- The panels' color has considerable impacts on photopic and melanopic units and color temperature of daylighting considered as main factors representing occupants' photobiological responses. Bluish panels were revealed increasing melanopic units and colder lighting temperature in the space which could potentially stimulate NIF responses. Red color panels were shown increasing photopic units and producing warmer lighting temperature which could potentially affect IF responses.
- The reflectance of panels' finishing could magnify the color behavior where matt surfaces' impacts on human-centric features are amplified all over the space compared to similar panels with a glossy finishing.
- The horizontal orientation of panels had considerably higher impacts on the daylighting parameters all over the space facing the south direction compared to the vertical orientation which had negligible influence especially on the area near the opening.
- Decreasing the openness between horizontal and vertical panels increases the impacts on daylighting features in the space and reduces the risk of glare in the scene.
- Future studies must investigate the human-centric performance of other colors with high and low reflectance under different daylighting conditions with different CCTs and sky types such as overcast skies.
- The panels' orientation impacts on daylighting must be investigated for other directions such as west and east, as the experimental setup designed towards south in this research.
- Future research could study the impacts of panels' size, form and openness variations on daylighting performance in terms of photopic and melanopic units and CCT.
- Further research must develop adaptive shading system to respond to hourly occupants' photobiological needs through modifying daylighting photopic and melanopic units and CCT in the space. Occupants' photobiological needs change hourly for different tasks and activities. Therefore, human-centric daylighting features must be adapted to occupants' photobiological lighting adaptation scenarios. This research argues that adaptive panels could be developed with different color sides and a controllable openness to operate manually or automatically in an hourly basis to address lighting adaptation scenarios in buildings. Such adaptive panels could modify daylighting features to meet hourly occupants' IF and NIF

needs for different tasks and in different climates. The adaptive panels could be developed with insulated materials to cover openings when daylighting is not required in the space in order to improve the building thermal performance in extreme cold climates.

3.8 Acknowledgment

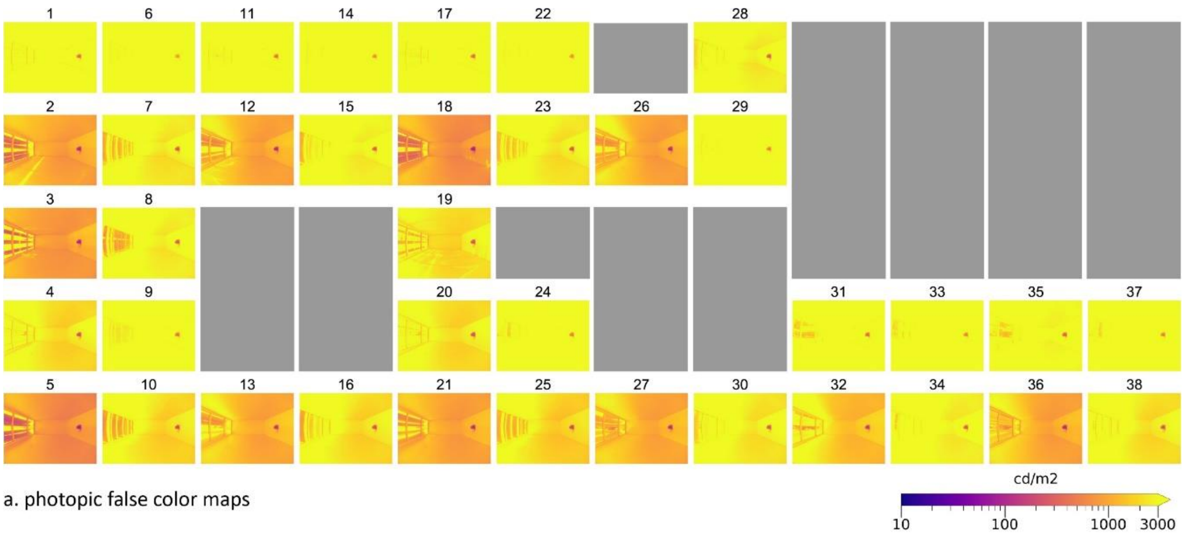
This research was supported by the Sentinel North program of Université Laval, made possible, in part, thanks to funding from the Canada First Research Excellence Fund.

3.9 Appendix 3.A

The courtesy of photos in Figure 3. 1 is as the following.

1. stylepark, University of Potsdam
2. Ernst Giselbrecht + Partner, Kiefer Technic Showroom
3. Claus Graubner, Coca Cola headquarters in Berlin
4. Mikou Studio, Florian Kleinefenn
5. Naud & Poux's Paris retirement home
6. Coltinfo, Marthashof Berlin
7. HAVER & BOECKER, Shands Children´s Hospital
8. Luc Boegly, CHL Social Housing
9. Schüco International, Cologne Oval Offices
10. Imagen Subliminal, Scientific and Technological Park of Cantabria

3.10 Appendix 3.B



a. photopic false color maps

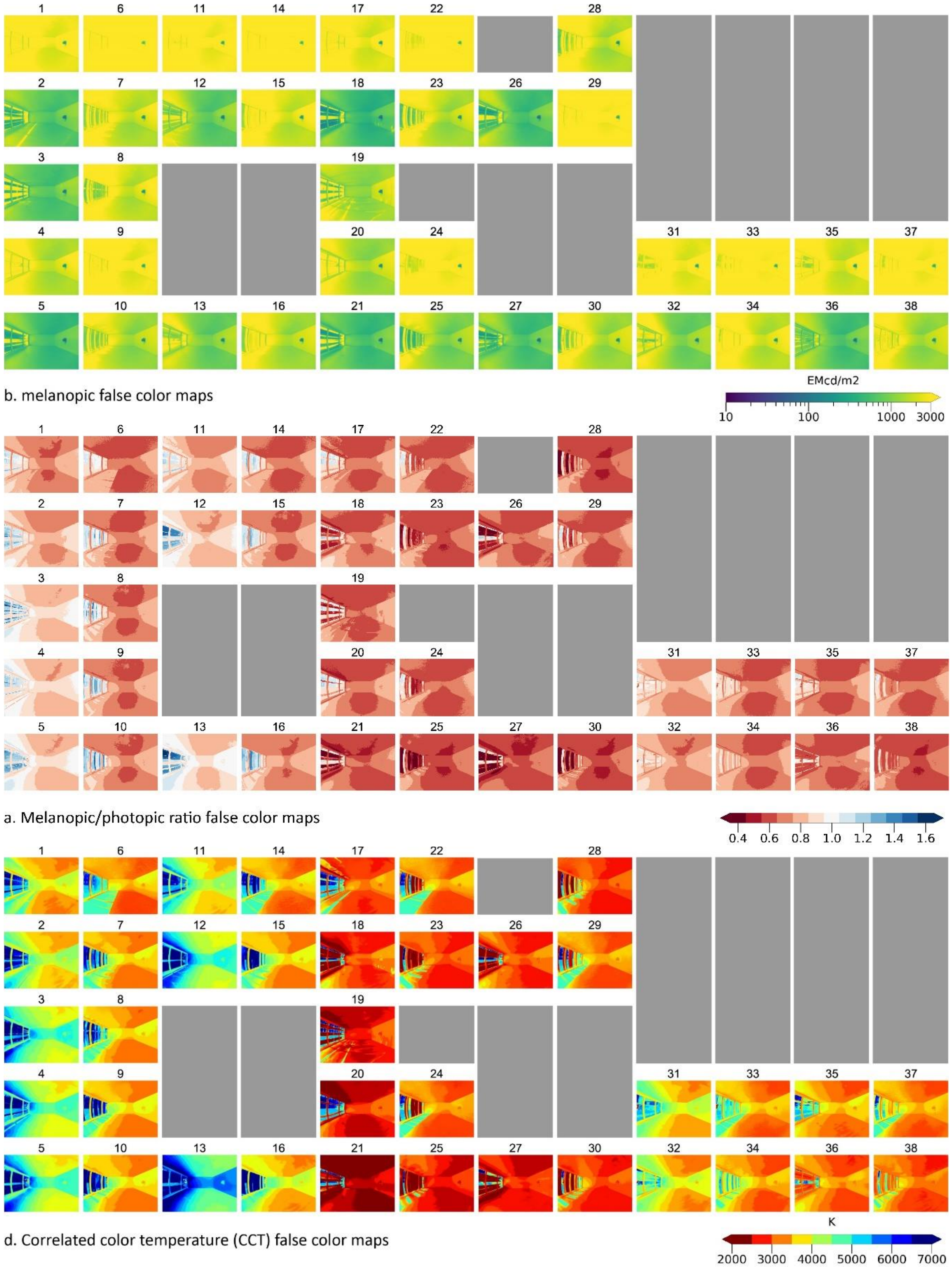


Figure 3. 14. The calculated false color maps of captured scenes from the side view in the model

Chapitre 4: Biophilic photobiological adaptive envelopes for sub-Arctic buildings

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4.1 Résumé

Les enveloppes des bâtiments doivent répondre aux besoins des occupants du Nord en matière de bien-être photobiologique et psychologique afin d'établir des relations positives avec la nature subarctique, notamment la lumière du jour et les cycles jour/nuit, au moyen de connexions intérieures/extérieures efficaces. Les configurations existantes des enveloppes des bâtiments du nord du Canada n'ont pas encore considéré les besoins des occupants en matière de bien-être photobiologique et psychologique pour des relations positives avec l'extérieur. Le potentiel des systèmes d'enveloppe adaptative pour répondre aux besoins photobiologiques et psychologiques des occupants des régions subarctiques n'a pas été étudié. Cet article développe un modèle fondamental d'enveloppes adaptatives multi-peau basé sur les principaux indicateurs biophiles et photobiologiques pour les bâtiments subarctiques afin de permettre des connexions efficaces intérieur-extérieur qui répondent aux besoins photobiologiques-psychologiques des occupants. Les indicateurs biophiles traduisent l'état des connexions entre les occupants et la nature extérieure, ce qui pourrait stimuler les réactions psychologiques potentielles. Les indicateurs photobiologiques déterminent des scénarios d'adaptation saine de l'éclairage pour une qualité d'éclairage horaire appropriée et une obscurité suffisante par rapport aux cycles jour/nuit locaux et à la lumière du jour. La performance de l'éclairage photobiologique a été évaluée par des méthodes expérimentales avec environ 23 modèles physiques à l'échelle 1:10. La performance biophile a été évaluée par plusieurs modèles numériques. Les résultats expérimentaux/numériques montrent que l'enveloppe proposée pourrait (i) offrir des connexions efficaces avec la nature extérieure au moyen de fenêtres de taille optimale pour la biophilie, et (ii) modifier les qualités de lumière du jour et l'obscurité à la période appropriée de la journée en fonction des besoins photobiologiques des occupants subarctiques horaires/saisonniers. Les potentiels et les défis du modèle d'enveloppe adaptative biophile-photobiologique proposé pour répondre aux besoins des occupants et à la performance des bâtiments dans des conditions climatiques subarctiques sont examinés, en particulier en termes de problèmes énergétiques liés aux modifications des fenêtres. Les résultats de la recherche fournissent aux architectes, biologistes et décideurs une perspective sur le bien-être des occupants et la santé des bâtiments dans les climats subarctiques.

4.2 Abstract

Building envelopes must address Northern occupants' photobiological-psychological wellbeing needs for positive relationships with the sub-Arctic nature, particularly daylighting and day/might cycles, through efficient indoor-outdoor connections. Existing envelope configurations of Northern Canada's buildings have not, yet, considered occupants' photobiological-psychological wellbeing needs for positive relationships with outdoors. Potentials of adaptive envelope systems to address sub-Arctic occupants' photobiological-psychological requirements have not been studied. This paper develops a fundamental model of adaptive multi-skin envelopes based on main biophilic and photobiological indicators for sub-Arctic buildings to enable efficient indoor-outdoor connections responding to occupants' photobiological-psychological needs. Biophilic indicators characterize the state of connections among occupants and the outdoor nature which could stimulate potential psychological responses. Photobiological indicators determine healthy lighting adaptation scenarios for proper hourly lighting qualities and sufficient darkness in relation to local day/night cycles and daylighting. Photobiological lighting performance was evaluated by experimental methods with approximately 23 1:10-scale physical models. Biophilic performance was evaluated by several numerical models. Experimental/numerical results show that the proposed envelope could (i) offer efficient connections with the outdoor nature through optimum window sizes addressing biophilia, and (ii) modify daylighting qualities and darkness at the proper time of the day adapted to hourly/seasonal sub-Arctic occupants' photobiological needs. Potentials and challenges of the proposed biophilic-photobiological adaptive envelope model to address occupants' needs and building performance under sub-Arctic climatic conditions are discussed especially in terms of energy issues related to windows modifications. The research outcomes provide architects, biologists, and decision-makers with a perspective towards occupants' wellbeing and healthy buildings in sub-Arctic climates.

4.3 Introduction

Building envelopes' configuration and windows are main elements connecting indoors to outdoors that must enable positive relationships between occupants and the harsh sub-Arctic nature (referring to near and above 50° northern latitudes towards the Arctic as Northern Canada in **Figure 4 | Supplementary.1**). Northern occupants' wellbeing requires positive relationships with the outdoor sub-Arctic nature, especially daylighting and seasonal photoperiods, i.e. day/night cycles, which are recognized as an influential environmental stimulus affecting psychological-photobiological responses [262, 263]. More specifically, occupants' relationships with nature, particularly outside buildings [264], is identified as ***biophilia*** [1-3, 5] which is acknowledged contributing to biological-psychological wellbeing [1, 19, 265, 266] by reducing stress, anxiety [6-8], boredom, irritation and fatigue [1, 9], increasing mental and cognitive performance, positive emotions and moods [10, 11], and regulating ***photobiological (light-related)*** rhythms as circadian clocks, or directly impacting alertness and sleep/wake cycles [85, 267]. Connecting building occupants to the sub-Arctic nature is, however, challenging because of extreme climatic conditions. Sub-Arctic climates offer very cold weather and drastic seasonal photoperiods resulting in very cold and short days in the winter and very long days with almost no darkness in the summer, creating polar days and midnight sun phenomena in very high-latitude regions [33, 262]. Northern daylighting conditions offer low-altitude sun lighting, e.g., lower than 50° around 60°-Northern latitudes, and bright diffuse daylighting of overcast skies especially in the winter when the white snow further diffuses and reflects lighting. The Northern daylighting color under clear and overcast skies is most often cool, above 6000 K, from the morning to evening [268-270]. Envelope configurations and windows are main elements modifying Northern occupants' exposure to the outdoor harsh nature which must provide positive efficient connections in terms of biophilia and photobiology [262, 263]. Envelope configurations and window sizes recommended by Canada national-provincial building and energy codes for Northern regions [136, 271, 272], however, neglect photobiological-psychological needs of occupants for efficient connections with nature. The main recommendations include tight envelopes with a low fenestration-and-door-to-wall ratio, i.e., around 20% (**Figure 4 | Supplementary.1**), aiming at reducing heat losses from fenestrations and decreasing the energy consumption of heating systems. Constructing tight buildings with a low fenestration-and-door-to-wall ratio minimizes Northern occupants' exposure to the outdoor nature, especially in terms of view and daylighting, increasing the risk of negative wellbeing impacts such as desynchronized internal body clocks, sleep disorders, depression, low physical and cognitive performance [41, 42, 126, 132, 182-185, 273], and sick building syndromes [274-276]. Previous studies also discussed the deficiencies of conventional single-skin and double-skin envelopes to respond to biophilic and photobiological requirements in Northern climates [263, 277]. Northern building envelopes must, therefore, foster efficient occupants' relationships with the outdoor harsh nature and address biological-psychological wellbeing requirements in addition to energy-efficiency factors.

4.3.1 General objectives and structure of the paper

This research develops a fundamental model of adaptive envelopes based on biophilic and photobiological indicators for Northern buildings which could address occupants' wellbeing in positive relationships with outdoors. Biophilic design guidelines characterize building features connecting occupants with nature in relation to potential positive wellbeing responses [278-280]. The photobiological (or human-centric) lighting approach articulates healthy lighting qualities required for internal body clocks and vision [12, 122, 281-283]. The adaptive envelope model proposed in this research is aimed at enabling efficient indoor-outdoor connections which could promote positive relationships between occupants and the sub-Arctic nature in terms of main biophilic and photobiological indicators. Approximately 23 1:10-scale experimental models to visualize lighting impacts through imagery techniques were combined with several numerical models to evaluate biophilic and photobiological daylighting performance of the proposed adaptive envelope configurations and windows under sub-Arctic climatic conditions. Details of prototypes, experiments and simulations are given in the methodology. Results of biophilic analysis are discussed in terms of provided potentials for efficient direct visual connections to the outdoor sub-Arctic nature which are related to potential biological-psychological responses. The paper also shows potentials of the proposed envelope to provide controllable, and sequential connections with the sub-Arctic nature. Experimental results of photobiological daylighting evaluations are discussed in terms of shading panels' surface characteristics' impacts on main photobiological indicators representing hourly/seasonal needs of occupants for proper daylighting qualities at the proper time of the day followed by sufficient darkness based on photobiological lighting adaption scenarios. The paper discusses potentials and challenges of the proposed biophilic-photobiological adaptive envelopes under sub-Arctic climatic conditions especially in terms of thermal and energy issues related to windows modifications. The paper, further, discusses potentials of intermediate systems enabling a thermal buffer system which could respond to thermal/energy challenges, as presented in the Appendix. Major issues and recommendations for future studies are outlined as conclusions. Results and discussions of the research draw attention of designers, architects, and policymakers to psychological-photobiological impacts of building envelopes on sub-Arctic occupants and potentials of adaptive envelopes to optimize biophilic and photobiological indicators combined with thermal/energy factors.

4.3.2 Background: Biophilic-Photobiological approach to envelopes

This research focuses on exposure and physical connections of Northern occupants to the outdoor nature, daylighting, and photoperiods through sub-Arctic building envelopes in terms of biophilic and photobiological indicators representing potential photobiological-psychological responses. Biophilia, the theory of humans' innate tendency to connect with nature and life-like cycles [1-3, 5], identifies the outdoor nature as the rich source of physical phenomena stimulating different biological responses and perceptual/cognitive phenomena [1-3, 5, 264]. Human-nature relationships are identified consisting of three main aspects including (a) physical natural phenomena as a source of sensory information, (b) potential biological responses and perceptual/cognitive phenomena, and (c) humans' exposure and physical connections to natural phenomena [1-3, 48, 280, 284]. Potential biological, photobiological, psychological, or perceptual/emotional responses of building occupants to natural phenomena are required physical connections and exposure to physical natural stimulus, particularly outside buildings [1-3, 48, 280, 284], which related fundamentally to envelope configurations and windows [1, 3, 285]. Hence, biophilic performance of sub-Arctic building envelopes could be evaluated in terms of potential humans' exposure to nature represented by the state of connections to physical natural phenomena and naturalistic features. Figure 4.1 illustrates the main biophilic performance indicators characterizing the state of connections to the outdoor nature and naturalistic features related to building envelopes. *Note that biophilic features of indoors, such as the use of greenery and natural materials for interior surfaces, are considered as a constant indicator which has remained unchanged as this research is focused on envelopes' performance. It is also assumed that potential occupants have healthy sensory systems to process, perceive, recognize, and experience different phenomena stimulated by exterior physical phenomenon*.

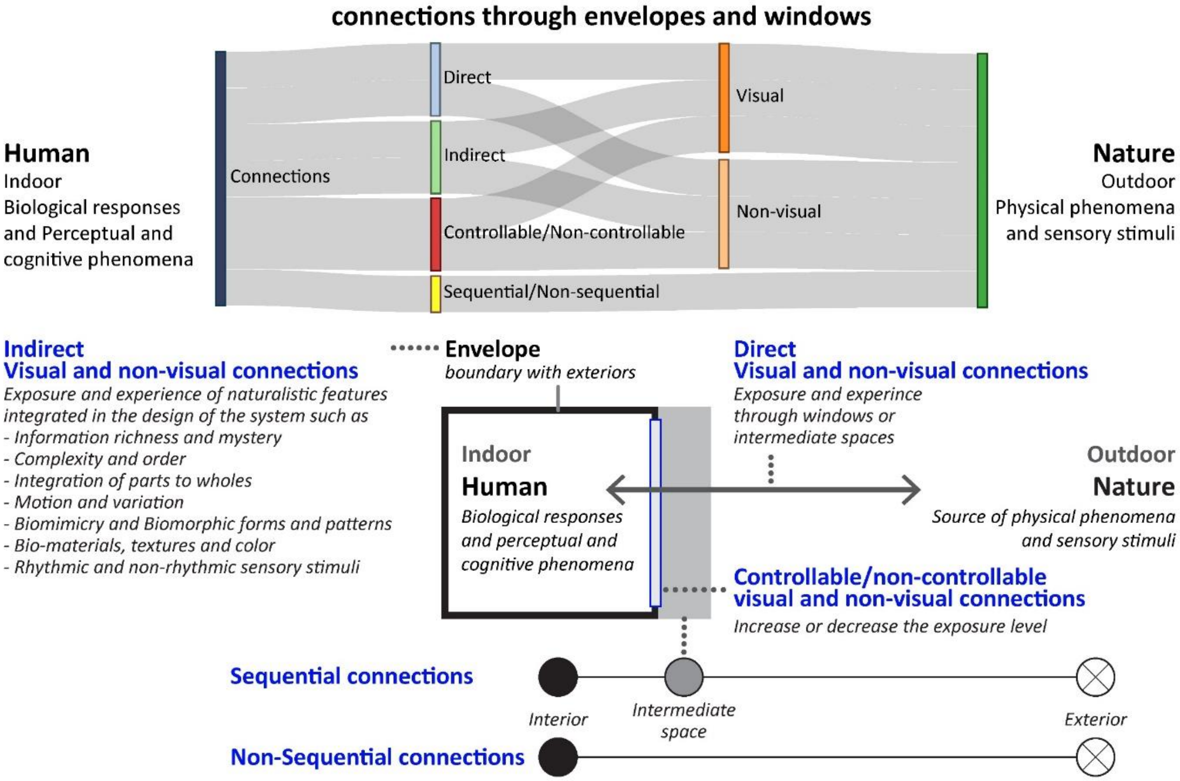


Figure 4. 1. Biophilic indicators representing the state of connections to the outdoor nature and naturalistic features related to building envelopes.

Direct visual connections to the outdoor nature are the main biophilic indicator of envelope configurations and windows. Direct connections expose occupants' sensory systems to outdoors which could enable visual/non-visual perception and experiences stimulated by different physical natural phenomena [1, 3, 285]. Exposure of the visual sensory system to physical natural phenomena dominates overall biophilic qualities of the space. The visual sensory system responses (i.e., eye's photoreceptors' signals) have a dominant influence over individuals' perception and cognition of surrounding environments and space [286, 287]. Proper visual sensory responses stimulated by natural phenomena could contribute to several physiological, photobiological and psychological wellbeing [13]. For example, visual connections and view to a natural element, scene or landscape could be restorative and reduce stress and anxiety [266, 288, 289]. Visual sensory system (eyes') connections to light/dark cycles could also entrain internal body clocks, known as circadian rhythms, and affect alertness and cognitive performance [12, 13, 262, 263, 290] (as further discussed in the following in terms of photobiological responses). Windows are the key component modifying occupants' direct visual connections to the outdoor natural phenomena [2, 285, 291]. Biophilic design, hence, calls for large window sizes to maximize direct connections with outdoors and immerse building occupants in the rich sensory environment of the outdoor nature [1, 3, 285]. Direct non-visual connections to outdoor natural phenomena through envelopes are also related to operable elements of windows which could enable natural ventilation (airflow and outdoor humidity and temperature), stream of nature sound and smell into space [1-3, 285, 291].

Controllable/uncontrollable connections through envelopes corresponding to strategies which control exposure of occupants' visual/non-visual sensory systems to outdoors. Under controllable connections, building occupants could control their visual/non-visual exposure to desirable, undesirable, or extreme sub-Arctic natural phenomena [1-3, 278, 280, 284]. For example, shading panels could control occupants' visual sensory (eyes) exposure to strong Northern photoperiods, snowstorms, gray overcast skies which enables controlling negative impacts of such phenomena on physiological, photobiological and psychological wellbeing. Sequential/non-sequential connections through envelopes are related to the spatial syntax depth and intermediate spaces such as corridors, porches, patios, and vestibules [1-3, 280].

Indirect visual/non-visual connections are discussed in terms of occupants' exposure to naturalistic features incorporated in the configuration of envelopes. The main naturalistic features are identified as nature-like complexity and order, integration of parts to wholes, biomimicry and biomorphic forms, shapes, and patterns, motion, and variation [1-3, 280]. Indirect connections are mainly analyzed through analogies between envelope systems and natural patterns and systems. Exposure of occupants' visual sensory system to, for example, biomorphic forms or complexity of envelopes could potentially recall their experiences of similar systems in nature [292]. Exposure of non-visual sensory systems to, for example, wood materials or texture used in envelope components such as window frames could potentially stimulate similar non-visual experiences with nature compared to plastic-based window frames [293].

In terms of photobiologic responses considered as the objective of the paper, photobiological impacts of lighting are recently discussed as the healthy lighting approach [262, 263, 283] by focusing on adapting photopic and melanopic units and color temperature of lighting to hourly photobiological needs of occupants for different activities in buildings [12, 93]. Photopic units, representing the photopic efficacy curve ($V(\lambda)$), characterize human eyes' image-forming (IF) responses enabling vision [13, 93, 94, 216, 283, 294] (see **Figure 4 | Supplementary.2**). Photopic units is conventionally discussed as illuminance in lux to explore visual comfort and glare in the space where an around 3000 lux in the field of view (FOV) is considered as an upper threshold limit for visual discomforts [216, 295-297]. Melanopic units, representing melanopic efficacy curve ($V^z(\lambda)$) [66, 68], and correlated color temperature (CCT) characterize non-image forming (NIF) responses of internal body systems to light received by eyes which affect circadian clocks with some direct impacts on sleep/awake patterns, alertness, and mood [12, 13, 57, 93, 216, 294] (**Figure 4 | Supplementary.2**). The analysis of melanopic/photopic (M/P) ratios combined with CCT has recently been proposed as an integrative or healthy lighting analysis approach to adjust potential IF and NIF responses [12, 93, 294, 298, 299]. In brief, a M/P-ratio of above 1 (M/P>1) means that the melanopic efficiency of a light source or a scene is higher than the photopic efficiency [93, 298, 300]. On the contrary, a M/P-ratio lower than 1 (M/P<1) indicates that the photopic efficacy of a light source or a scene is higher than the melanopic efficiency [93, 298, 300]. The higher M/P-ratio corresponds to a higher melanopic efficiency whereas lower M/P-ratio corresponds to a higher photopic efficiency [93, 298, 300]. Photobiological studies state that lighting qualities in terms of photopic, melanopic units and color temperatures must adapt to hourly IF/NIF needs of occupants [13, 262]. The general photobiological lighting recommendation include cool (blue-enriched) high-intensity lighting for at least two hours in the early morning and warm low-intensity lighting in the afternoon and evening, especially two-hours before sleeping, followed by almost complete darkness during the biological night, i.e. considered from 7pm to 7am (for further details, refer to [57, 65, 93, 241, 263, 301]).

4.4 Adaptive envelope model for biophilia and photobiology

The research proposes a fundamental model of adaptive multi-skin envelopes consisting of three elements which play key roles in modifying biophilic, healthy lighting, and thermal/energy performance of Northern buildings [262, 263, 283]. As illustrated in Figure 4.2, the proposed envelope model includes **(i)** an efficient window size (opening) for the interior skin, **(ii)** dynamic shading panels made of (super-) insulation materials sandwiched by colored wood sheets which are installed adjacent to the window and can move or rotate around horizontal or vertical axes, and **(iii)** a thermal buffer system made of an operable glazing skin. The hypotheses and objectives formulated for the proposed configuration and elements are summarized as the following. *Biophilic and photobiological* performances of the proposed envelope model are evaluated and discussed in this paper.

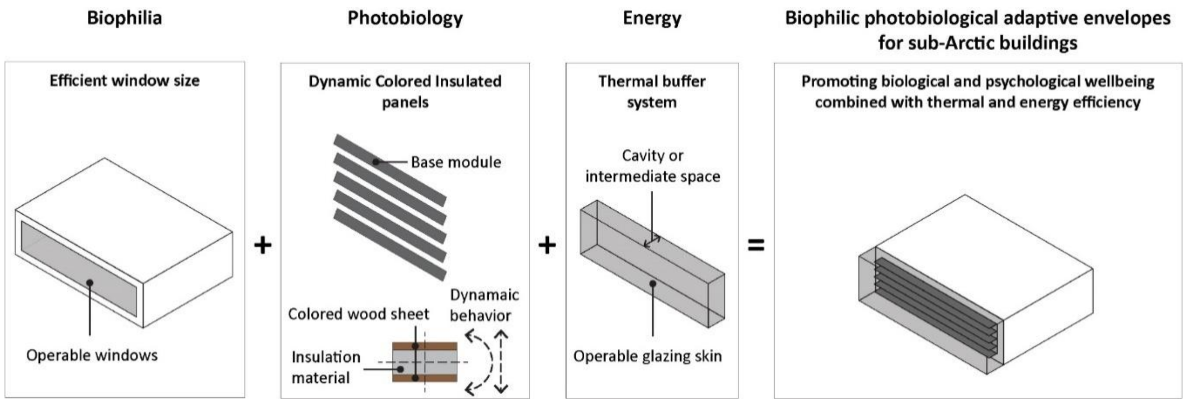


Figure 4. 2. The proposed biophilic-photobiological adaptive envelope model including essential components and configurations.

4.4.1 Optimum window sizes to promote biophilia

The efficient window size is aimed at optimizing occupants' connections with the outdoor nature in terms of biophilic indicators. Considering the states of occupant-nature connections related to envelopes (Figure 4.1), the window size determines occupants' FOVs to outdoors which could affect potential direct visual experiences of the outdoor nature, as the main biophilic indicator [1, 3, 285]. Efficient window size variables for visual connections to outdoors are related to the window-to-wall ratio (WWR), window-to-wall-length ratio (WWLR) and window-to-wall-height ratio (WWHR) which could modify occupants' horizontal-FOV (h-FOV), vertical-FOV (v-FOV) and overall FOV in different depths (spots) of space towards outdoors. The efficient window size and FOVs could establish effective direct visual connections between occupants and the outdoor nature. As this research aimed at promoting wellbeing related to biophilia, the efficient biophilic window size for higher biophilic performance in terms of immersive connections with the outdoor nature is computed, then, combined with the shading panels and thermal buffer system to control and optimize occupants' exposure to outdoors as well as building's lighting, thermal and energy performances.

4.4.2 Dynamic-colored-insulated shading panels focused on photobiology

The dynamic-colored-insulated shading panels are aimed at improving (i) photobiological-psychological wellbeing related to healthy lighting and controllable exposure to sub-Arctic photoperiods and harsh (undesirable/extreme) natural phenomena, and (ii) thermal/energy performance by controlling heat losses from windows. The research hypothesized that panels' surface characteristics, including color, reflectance, orientation, inclination, density, size, and positions at openings, could modify healthy daylighting parameters. The spectral power of surfaces' color and reflectance could, particularly, modify the daylighting spectral power and efficiency of different spectrums related to photopic and melanopic functions (**Figure 4 | Supplementary.2**)[139, 251, 283, 302, 303]. Colored panels with dynamic behaviors to move vertically/horizontally, rotate or flip upwards/downwards/left/right could control occupants' exposure to Northern drastic photoperiods and natural phenomena affecting photobiological-psychological wellbeing. The dynamic-colored panels could potentially modify the distribution and intensity of healthy daylighting parameters in the space to meet hourly photobiological needs of occupants. The dynamic panels could also cover openings and block daylighting when lighting and exposure to outdoors are not required indoors, for example, during 24 hours of weekends or unoccupied times for Northern office buildings or during bright evenings of Northern summers (polar days) for residential buildings or sleeping areas. The dynamic panels for covering windows are considered to be made of (super-) insulation materials to prevent potential heat losses and reduce energy demand. The openings' blockage during nights could also prevent interiors' lighting emissions to outdoors as a potential source of nighttime lighting pollution, especially during the winter with a reflective snow-covered ground. The modulated colored panels with dynamic behaviors ultimately address indirect connections to nature, as a biophilic indicator, for example, by imitating natural patterns, order, complexity, and color.

4.4.3 Thermal buffer for potential thermal/energy efficiency

The thermal buffer system is aimed at improving thermal performance and energy efficiency of Northern buildings by controlling heat losses/gains from the façade and windows. Reducing the energy consumption of Northern buildings generally demands a low WWR to decrease heat losses from windows, as recommended by Canadian building codes [136, 271, 272]. However, biophilic design recommends immersive connections with the outdoor nature through windows [1, 3, 285]. which pose energy challenges under extreme cold Northern climates. The research is, therefore, hypothesized that the thermal buffer system made of an operable glazing skin could act as a controllable greenhouse which could trap solar heat during the Northern cold weather and enable efficient natural ventilation in the winter/summer. four fundamental configurations of intermediate spaces could be a (i) window-size cavity, (ii) façade-size cavity, (iii) façade-size transient intermediate space similar to covered corridors, and (iv) façade-size habitable intermediate space similar to covered balconies/porches. The transient/habitable intermediate space is hypothesized that could contribute to biophilic performance by providing a protected transparent place fully exposed to the sub-Arctic nature in which individuals could safely move, stay, relax, or rest. *The focus of this paper is to explore the biophilic and photobiological impacts of the proposed envelope. Hence,* *developing an advanced thermal buffer system, such as made of high-thermal-performance materials and windows or heat storages, are not discussed. Yet, an appendix is added to the paper to give a perspective towards potentials of intermediate spaces with typical thermal properties and different in-between depths to provide a thermal buffer system which could respond to challenges of modifications in windows sizes of sub-Arctic buildings. Developing high-thermal-performance intermediate spaces based on the biophilic-photobiological adaptive envelope model is the objective of future study and publication.*

4.5 Methodology

4.5.1 Biophilic performance evaluations of the adaptive envelope

As the main biophilic indicator representing direct visual connections to outdoors, the research evaluated impacts of different windows and horizontal/vertical shading panel sizes of the envelope on occupants' FOVs in different depths of space towards outdoors. Window size variations included 20% WWR, as recommended by Canada building codes for Northern climates [136, 271, 272], to 100% WWR, which could be provided by 30% to 100 of WWLR and 40% to 100 of WWHR, as shown in results-Figure 4.5. Variations of horizontal/vertical panels' size are also evaluated from 20 to 80 cm, similar to small to extreme large models used in different buildings (see examples presented in [263, 283]). Occupants' FOVs are analyzed in numerical models of a reference open-space office (see **Table 4 | A.1**), as a case study, with different window sizes in terms of horizontal, vertical, and overall view angles towards the window and outdoors. View angles of a potential observer in the space were calculated from several viewpoints on horizontal and vertical plans (see results- Figure 4.5). The viewpoints represent individuals' FOVs towards outdoors in the entire space from the back corner to the middle and front close to the window. The space is assumed to be symmetric in terms of the window position. Hence, the view angle from the spots closer to the left-side wall is similar to viewpoints closer to the right-side wall. The horizontal and vertical view angles were derived by using triangular calculations with respect to Hellinga and Hordijk [304], European Committee For Standardization (CNE) [305]. The view angles for different panel sizes were calculated for the case of 80% WWLR and 67% WWHR from the middle and corner near the back wall as the highly obstructed viewpoints to outdoors. The calculated view angles were, then, normalized by the typical human eyes' view angles accounted as about 120° for horizontal and vertical view angles. The overall FOV in different viewpoints were calculated by multiplying horizontal and vertical FOVs in relation to distance to the central point of the window which is normalized to the corresponding value for the overall human eye's FOV in an unobstructed outdoor environment.

The research evaluated controllable visual connection abilities of the proposed envelope in terms of the potential of dynamic panels to control occupants' connectivity and exposure to outdoors. The openness ratio among panels is the key factor representing indoor-outdoor connectivity and exposure levels. Horizontal panels are considered having abilities to rotate/flip/move around a horizontal axis from -90° downwards or +90° upwards (completely close) to 0° (completely open), as illustrated in results- Figure 4.7. The openness ratio of horizontal panels was calculated by generating and post-processing views of a potential observer in the middle of space towards outdoors with the window size of 60% WWR, 90% WWLR and 67% WWHR. Two scenarios of moving all the panels to the top and bottom of the window were also evaluated. The envelope and window with no panel and exposure in the intermediate space (habitable/transient) were also considered which showed the maximum possible visual connections enabled by the window size and envelope configuration. The views were generated as images by using Rhino-Grasshopper software. The generated views were, then, post-processed in a black and white mode. The ratio of open (white pixels) to obstructed (black pixels) areas offered in the window frame was determined as the openness ratio correlated to connectivity and exposure values to outdoors. The maximum ratio of 1 refers to the case with no obstruction in the visual field corresponding to maximum indoor-outdoor connections enabled by the widow and intermediate space. The minimum ratio of 0 refers to the case with the completely blocked window disconnecting occupants and indoors from outdoors.

The biophilic qualities of the proposed envelope were also discussed in terms of complexity and order in the spatial syntax and geometry. The spatial syntax complexity is corresponded to deeper levels of spatial graphs and higher functionality and usability of spaces. The envelope model proposed with a transient or habitable space addresses sequential connections and offers a deeper spatial syntax, as illustrated in results- Figure 4.7. The spatial syntax graph methodology [306, 307] was used to assess the proposed envelope models. The geometric complexity is related to higher components and elements such as shading devices and multi-skins integrated in the envelope compared to a conventional plain façade. The dynamic behavior of components such as shading devices, offering different compositions and variations, is considered relating to higher complexity of the systems as well as imitated motion and variation in nature. The biomimicry of natural patterns and colors such as different colors of skies and landscape or day/night cycles is also included as indirect connections to nature-like systems which could stimulate visual sensory modalities such IF and NIF responses.

4.5.2 Photobiological lighting evaluations

4.5.2.1 Experimental setup and scale model

An experimental setup was designed to measure and analyze healthy parameters of daylighting inside a 1:10 physical scale model of an open-space office under real sun lighting and diffuse overcast lighting of artificial skies. Physical models are commonly used during the architectural design process to provide a comprehensive understanding and visualization of lighting conditions in the space identical to lighting performance of a real scale building [187, 253]. As illustrated in Figure 4.3, the physical scale models of this research were made of wood painted in glossy varnished cool white color for the ceiling, glossy varnished cool white for walls, matt varnished gray color for the floor, and a double-glazing window with a 12 mm air cavity and about 70-80% visual transmittance. The surface visual reflectance (LVR) and varnished specularity (SV) values are presented in **Table 4 | Supplementary.1**. The dimension and proportion of the model were verified based on previous studies of Poirier, et al. [35], Jafarian, et al. [36], [140]. Two Raspberry Pi's with fisheye-lens cameras were installed on the side and back walls to capture and analyze lighting conditions inside the model, as explained in the following. The model was constructed with completely sealed joints to prevent light leakage as underlined by Ruck, et al. [187], Baker, et al. [253]. The base model, which has 100% WWR with no panel, is considered as the reference, Case-0, which enables discussing the impacts of colorful panels on daylighting features inside the space.

4.5.2.2 Experimental procedure

Experimental evaluations were conducted under actual and artificial daylighting and skies conditions identical to sub-Arctic climates. The experimental evaluations of the panels were performed towards the south direction under real clear skies (0-1 of cloud cover scale) with direct sun lighting from 10:30 to 14:30, October 26, 2019, in Quebec, CA, as illustrated in Figure 4.3. All panels were built before the experiment and were designed to be simply installed in front of the model. Two persons have set up the experiment, changed panels' configuration and performed the measurements. Changing panels took less than 60 seconds which helped considerably saving time. Transporting the model and panels to outdoors and preparing the experimental setup under real skies were started from 7:30. Few preliminary tests were performed to adjust the setup which took about 30 minutes. The experiments were started around 10:30 and finished around 14:30. As shown in Figure 4.3, the vertical illuminance (E_v) and color temperature (CCT) of exterior lighting in the direction of the model were recorded every 30 minutes during the experiment by using Konica CL-200A Chroma Meter. The sky cloud cover as well as the intensity and color of sun lighting remained relatively stable during the experiment. The solar geometry had negligible impacts on the experiment under such lighting conditions and experiment period. The similar experimental setup and scale models were also used to perform further measurements under artificial skies offering diffuse lighting with very cool to very warm color temperatures identical to daylighting conditions in Northern Canada. Artificial skies have widely been used to evaluate the configuration of the space such as the surface color and reflectance, size and form of window, skylight openings, and shutters and louvers performance (for example see [187, 253, 303]). The experiments were performed under three artificial sky lighting conditions with 5700, 4400 and 2800 K, about 4000 lx horizontal illuminance (E_h) and 1500 lx vertical illuminance (E_v) received at the height of the model (Figure 4.3).

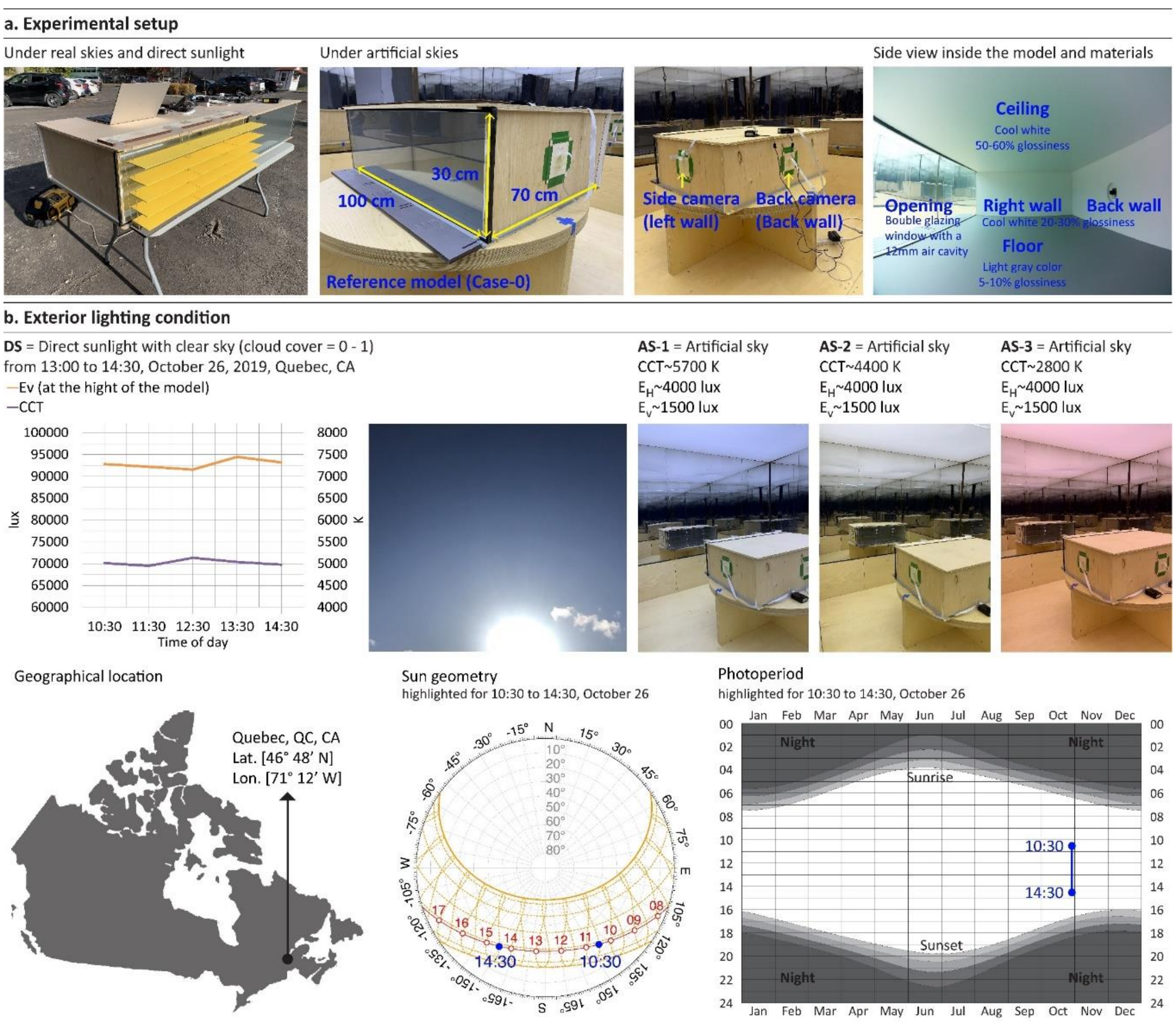


Figure 4. 3. Experimental setup and exterior lighting conditions, identical to Northern conditions, to measure and evaluate the lighting performance of panels inside 1:10 scale models of an open-space office in Quebec, CA, as a case study.

4.5.2.3 Panels' configurations and prototypes

This research evaluated the main characteristics of shading panels which could modify healthy daylighting parameters including color, reflectance, orientation, inclination, density, size, and position, as shown in Figure 4.4. Approximately 23 different prototypes of panels were built at a 1:10 scale. Eight prototypes were built in different colors, including strong and light blue, strong green, yellow-green, strong yellow, strong red, cool white and warm white, with an unvarnished matt finish, less than 5% SV (as given LRVs and SVs in **Table 4 | Supplementary.1**). Eight prototypes were built with similar colors and a varnished glossy finish, around 20-30% SV (as given in **Table 4 | Supplementary.1**). Four prototypes were built with different colors on each side including strong blue-strong red and light blue-strong yellow with matt and glossy finishes. Each two-color side panels' set was evaluated in two different configurations by flipping the panels. Three prototypes were built in different sizes with a matt strong blue color, as shown in Figure 4.4. Optical properties of materials including surfaces' color and reflectance can potentially modify spectral power density of daylighting corresponding to different human eyes' biological responses related to photopic and melanopic efficacy curves (see previous studies in [139, 248, 283, 302, 303, 308]). The panels' colors were chosen to be enriched in different spectrums based on the test color sample (TCS) spectrums provided by Waveform Lighting [309], as displayed in **Figure 4 | Supplementary.2**. The panels are designed to be installed in a horizontal orientation with +30° upwards to -30° downwards inclinations (Figure 4.4) studied under direct sun lighting and diffuse overcast lighting. The vertical orientation of panels was not studied under the south direction direct sun lighting as previous research has shown that the vertical orientation does not affect the south direction sun lighting distribution and penetration in the space [283]. The vertical panels with 0 to 30° left inclinations were evaluated under diffuse lighting of artificial skies. Note that the left or right inclination of vertical panels under diffuse lighting potentially produces a symmetric lighting performance. Hence, vertical panels were evaluated in a fold behavior as V-shape which could hypothetically produce different lighting performance (Figure 4.4). Lighting impacts of panels' density were evaluated in terms of the horizontal panels installed in a high density, five rows, or a low density, three rows, relevant to the 1:10 scale of the studied model. Lighting impacts of panels' position were evaluated in terms of horizontal panels installed at the top or bottom position with upwards or downwards inclinations in relation to the opening (Figure 4.4). Considering the research hypotheses, nine experiment scenarios were determined to evaluate the impacts of panels' variables on lighting parameters inside the space under different exterior lighting conditions as illustrated in **Table 4 | Supplementary.2**.

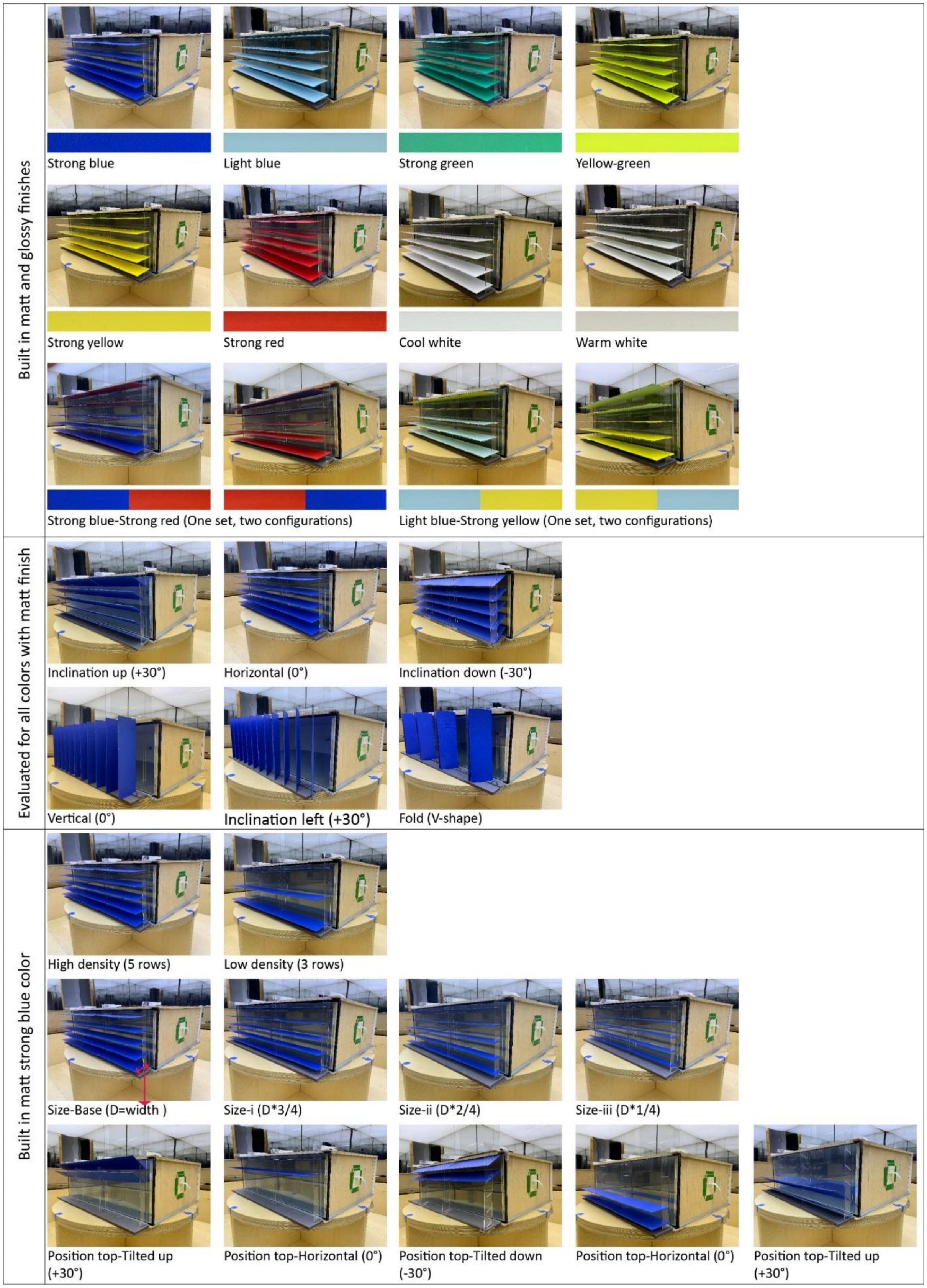


Figure 4. 4. The case studies of panels with different configurations

4.5.2.4 Lighting measurements and analysis

Photobiological lighting evaluations of panels were done through high dynamic range (HDR) imagery and post-processing techniques to calculate and render false color maps of lighting photopic and melanopic units, M/P-ratios and CCTs inside the scale model. Recent developments of HDR imagery and post-processing techniques enable evaluating such lighting parameters within the camera's FOV [209, 216, 259]. HDR imagery is, generally, identified as a useful and accurate method to visualize and comprehend lighting conditions in the building and architectural space [209, 259, 310]. Multiple low dynamic range (LDR) images from very dark, nearly -3 exposure value (EV), to very bright, nearly +3 EV, were captured by two Raspberry Pi cameras from side and back views (**Figure 4 | Supplementary.3**). The Pi cameras were mounted with fisheye lenses with around 170° field of view similar to human eyes' FOV. The server, a portable computer, run a python script initiating Pi's camera module to capture LDR images (**Figure 4 | Supplementary.3**). Capturing and storing LDR images took about 60 seconds. The captured LDR images were, then, merged and calibrated to generate HDR images based on previous studies recommending to discard over- and under-saturated images [258-260] and adjust RGB (Red, Green, Blue) and XYZ (CIE tristimulus) channels [76, 216]. The calibrated HDR images were post-processed to calculate per-pixel photopic, melanopic, M/P ratio and CCT values based on studies of Jung [76], Jung and Inanici [216]. The photopic intensity distribution of captured scenes were plotted in a false color format with a logarithmic scale in cd/m2 with a threshold of 3000 representing glare probabilities [213, 261]. False color maps of melanopic intensity distribution were also plotted for the captured scenes in a logarithmic scale in EM cd/m2 [76, 216]. False color maps of lighting CCT distributions were generated based on the McCamy method [76, 216] for all scenes in a range of 2000 K (very warm) to 7000 K (very cool). The M/P-ratio distribution of the captured scenes were rendered in a false color map format and violin plots. M/P-ratios' violin plots enable evaluating prototypes in terms of the frequency and accumulation of higher and lower M/P-ratios in the scene [283].

4.6 Results and discussions

4.6.1 Biophilic performance of the envelope

Results show that the proposed envelope could promote biophilic performance of Northern buildings evaluated for a reference open-space office through numerical-analytical methods. As the main biophilic indicator, the proposed envelope was optimized for efficient direct visual connections to outdoors related to occupants' FOVs, windows and shading panels. Occupants' FOVs were calculated for several viewpoints, from the back corner to the middle front close to the opening, in numerical models of the reference office space with different window and horizontal/vertical panel sizes. Figure 4.5 shows the calculated non-normalized horizontal and vertical view angles for different sizes of widow and horizontal/vertical panels. As shown in Figure 4.5, the individual's h-FOV in the space with 80% WWLR is less than 10° smaller than the corresponding h-FOV in the space with 100%% WWLR. The h-FOV is significantly obstructed by decreasing the WWLR to 60% and lower. The individual's v-FOV in viewpoints near the back wall decreases around 10° by changing the WWHR from 100% to 60%. The calculated view angles were normalized and synthesized in Figure 4.6 indicating the window size in the range of 60%-WWR, 90%-WWLR, and 70%-WWHR, with a ±10% tolerance, could offer optimum h-FOVs, v-FOVs, and overall FOVs to outdoors compared to the maximum possible FOVs enabled by the space and façade dimensions. As illustrated in Figure 4.6-b, FOVs' probabilities enabled by the optimum window size range are almost close to FOVs' probabilities of larger windows, for example 70% to 90% WWRs. Decreasing the window size to lower than the optimum range, for example 40% to 20% WWRs, considerably obstructs occupants' FOVs to outdoors (Figure 4.6-a and b). The size of horizontal shading panels has slight impacts, around 5%, on obstructing the occupants' h-FOV and v-FOV. As illustrated in Figure 4.5, increasing the size of horizontal panels by eight times, from 10 cm to 80 cm, reduces the h-FOV around 5° for individuals located near the back wall in the middle or corner of the space compared to the reference model with no panel. The eight-time increase of the horizontal panels' size reduces the v-FOV about 5° for viewpoints near the back wall compared to the reference model. The size of vertical shading panels has considerable impacts on obstructing the occupants' h-FOV, up to 20%, and slight impacts on the v-FOV, about 5%. As depicted in Figure 4.5, increasing the vertical panels' size by eight times, from 10 cm to 80 cm, reduces the h-FOV up to 20° for individuals near the back wall in the middle or corner of the space compared to the reference model. The eight-time increase of vertical panels' size reduces the v-FOV of individuals near the back wall about 5° compared to the corresponding value in the reference model.

The envelope configuration for Northern buildings is, therefore, proposed with the optimum-size window and horizontal panels which could enable efficient direct visual connections for potential positive biological responses and perceptual/cognitive phenomena stimulated by the outdoor nature. In the context of a diverse Northern landscape with plants and different ground covers or daylighting, day/night cycles, cloudy/clear skies, efficient FOVs by the optimum-size operable window can potentially enable healthy occupants to see the landscape and outdoors phenomena, and perceive different features such as the diversity, complexity, light, color, motion and daily/seasonal variations in plants, light, and sky.

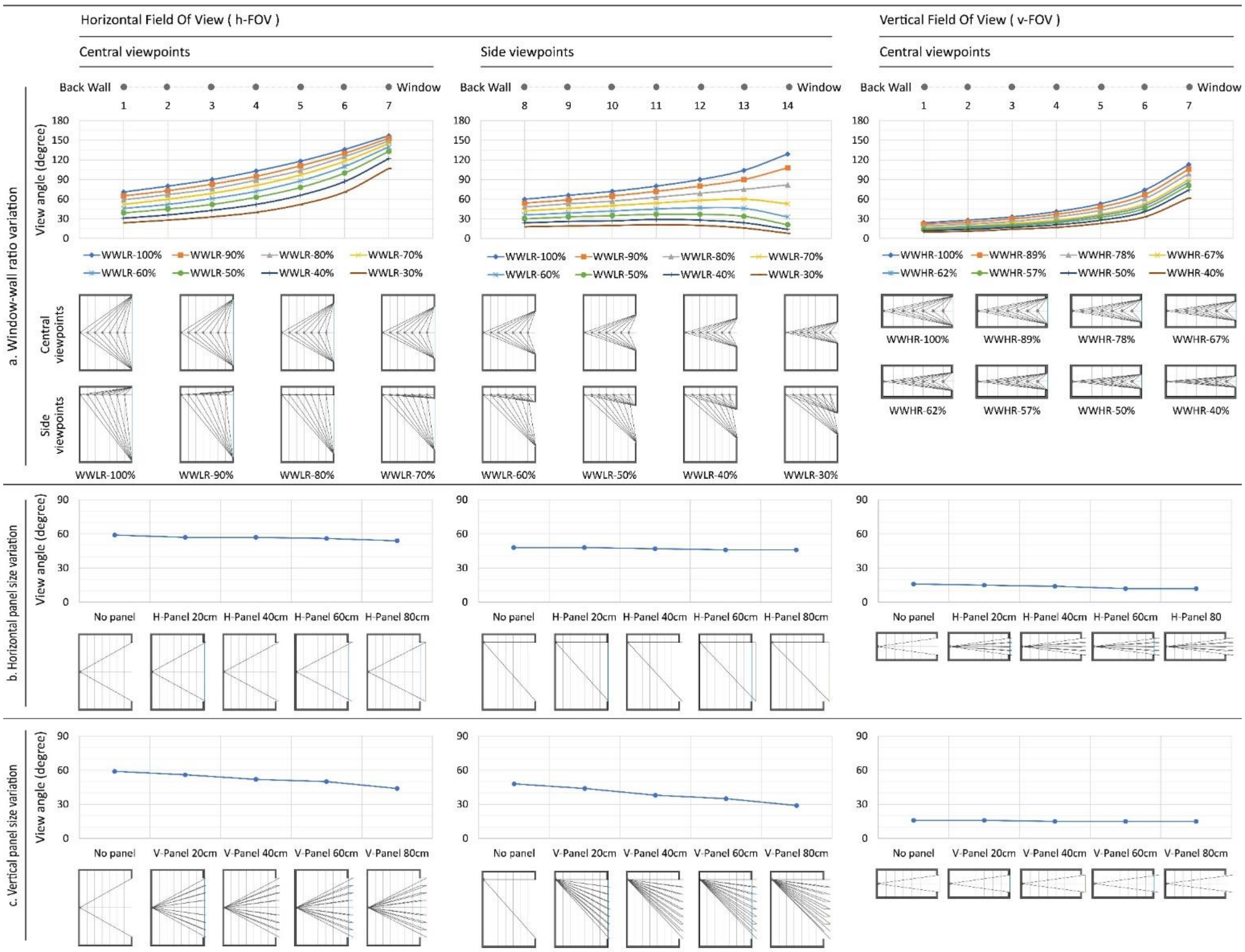


Figure 4. 5. Impacts of different sizes of (a) window and (b) horizontal, and (c) vertical panels on the individual’s horizontal and vertical field of views (FOVs) from different viewpoints in the reference office.

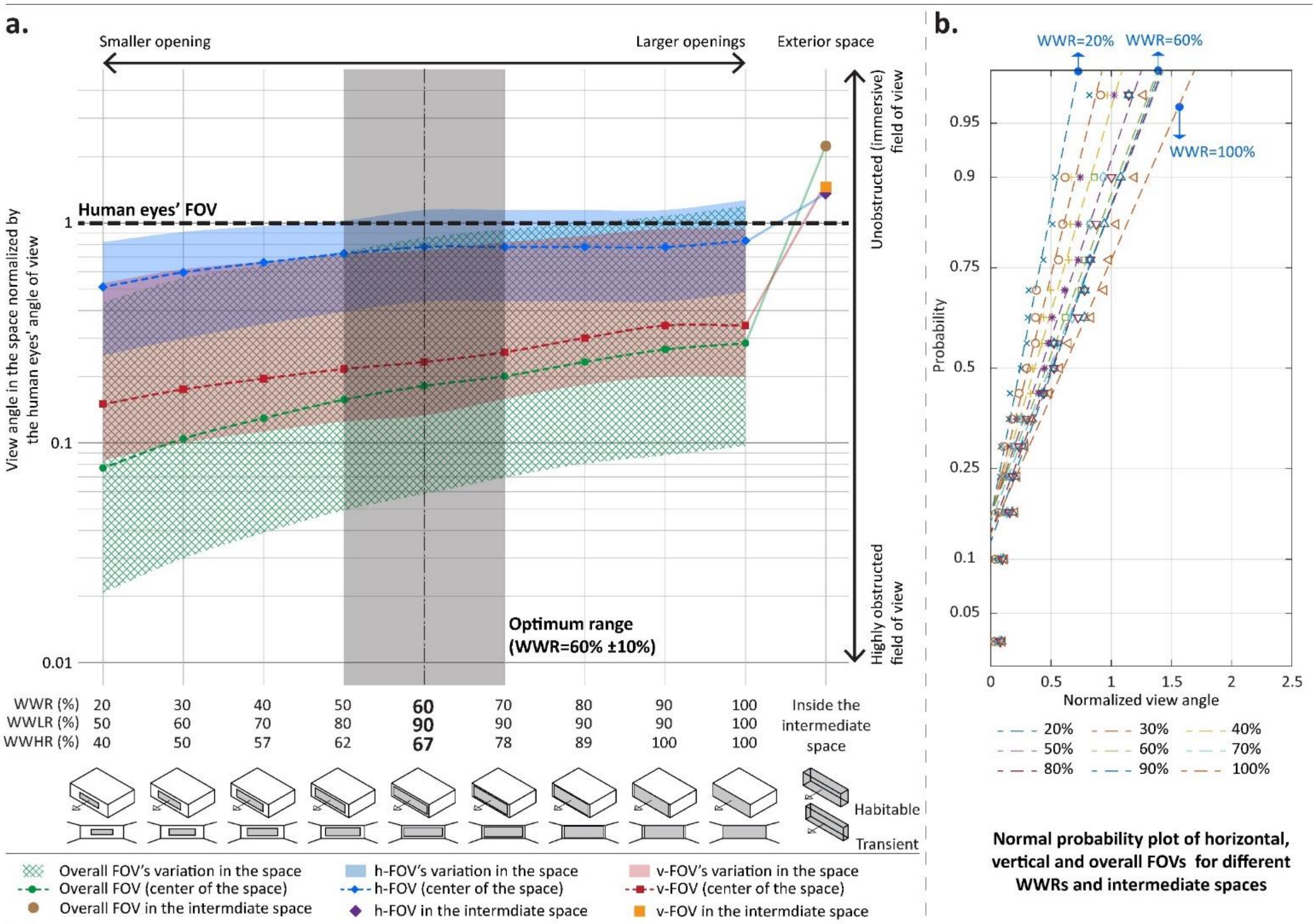


Figure 4. 6. (a) occupants' horizontal, vertical, and overall field of views (FOVs) to outdoors normalized to the human eye's view angles in relation to different window sizes (WWR, WWLR, and WWHR) and habitable/transient intermediate spaces. (b) normal probability plots of occupants' field of views for different window sizes and intermediate spaces.

Combining the efficient window size with dynamic panels offers controllable visual/non-visual connections to outdoors which allows modifying occupants' exposure to different desirable/undesirable-extreme natural phenomena. As illustrated in Figure 4.7-a, the dynamic panels with different openness ratios control the indoor-outdoor connectivity and occupants' exposure levels to the outdoor nature as the rich sensory environment. Increasing the openness among panels increases the indoor-outdoor connectivity which exposes occupants to the (desired) outdoor natural phenomena. Whereas, reducing the openness decreases indoor-outdoor connections which could (fully-) disconnect/cover occupants from the (undesired) extreme sub-Arctic phenomena such as drastic day/night cycle or wind/snowstorms.

In the case of transient/habitable intermediate space, occupants are fully exposed to the outdoor nature and immersed in the outdoor sensory environment. The transient/habitable intermediate space offers occupants with unobstructed immersive FOVs to outdoors (see Figure 4.6). Occupants are directly connected to the Northern natural phenomena in a protected transient/habitable intermediate space where they could visually/non-visual perceive different phenomena during a short or long move, stay or rest. The intermediate space with operable glazing skin could enable natural ventilation during the desirable weather of summer which is further improve biophilic qualities in terms of non-visual connections with nature. The transient/habitable intermediate space also creates a sequential spatial syntax to connect with the outdoor nature (see Figure 4.7-b) improving biophilic performance of the building.

Compared to the conventional simple façade of the reference model offered by Canada building codes, the overall configuration of the proposed envelope increases indirect visual/non-visual connections to naturalistic features. The proposed envelope with the dynamic panels and thermal buffer system increases the complexity and order of spatial syntax and geometries, as illustrated in Figure 4.7. The panels are modulated to create a whole by duplicating a base module over the façade which combined with a dynamic behavior to move/rotate in different axes similar to natural patterns where a base form is duplicated to create a whole dynamic surface. Occupants are offered to experience the sense of variation and motion stimulated by the panels' dynamic behavior. As depicted in Figure 4.7-c, colored panels could imitate Northern daylighting and skies by creating different color spectrums inside the space. Imitated color schemes and day/night cycles could stimulate and adjust photobiological responses as explained in the following section.

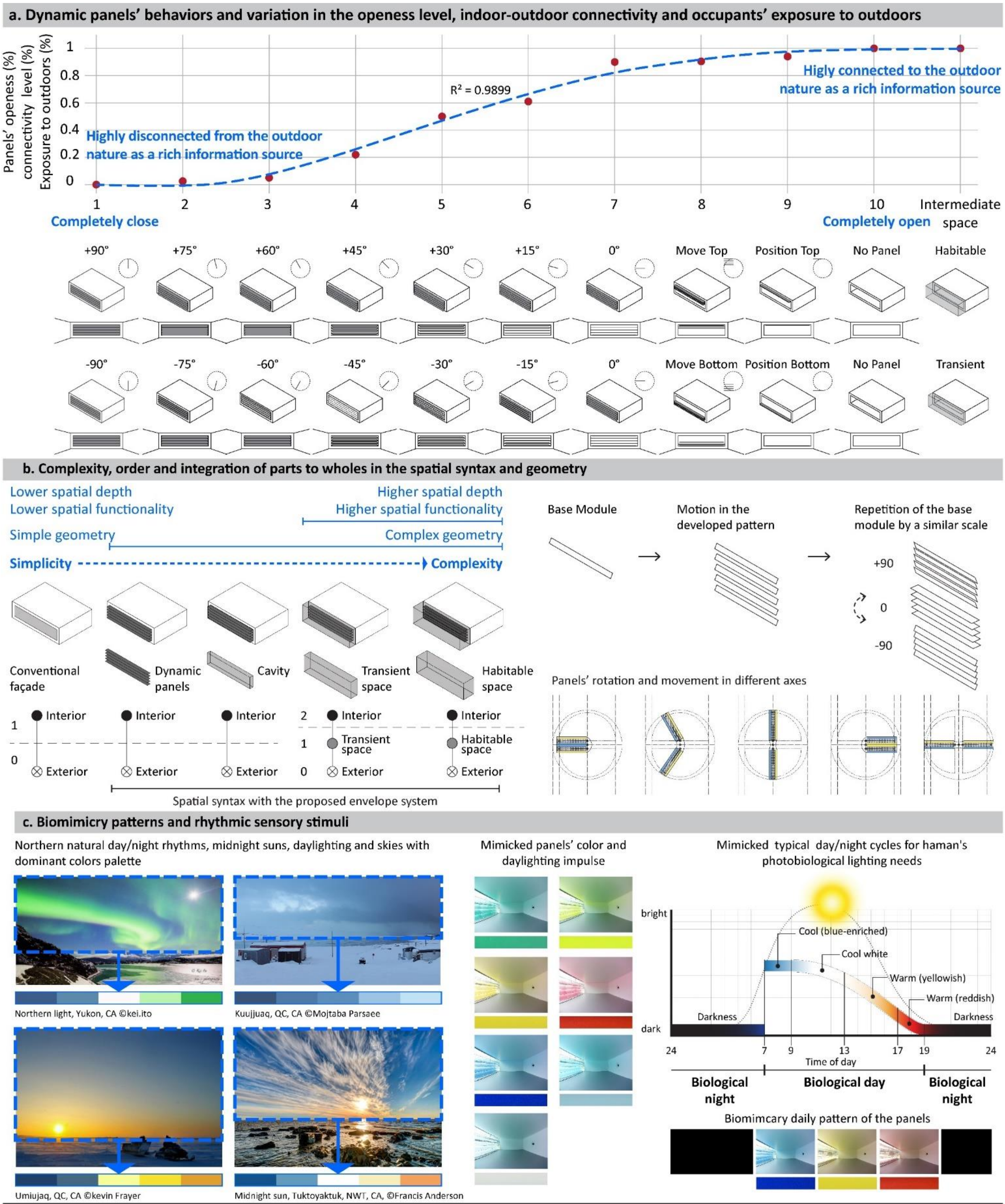


Figure 4. 7. (a) Connectivity to outdoors affecting the information richness value, (b and c) analogy between the proposed envelope configuration and natural systems and phenomena representing indirect connections with nature.

4.6.2 Photobiological lighting performance of the biophilic envelope

The experimental results show the potentials of panels to adapt Northern daylighting photopic and melanopic units and color temperatures to occupants' hourly photobiological needs. The results of experiments are presented in terms of the photobiological lighting performance of panels' surface variables under different exterior lighting conditions identical to Northern daylighting. The results are, then, synthesized to adjust panels to lighting/thermal adaptation scenarios addressing photobiological needs of occupants in the reference office. The lighting performance of the reference model, Case-0, is illustrated in Figure 4.8 to enable identifying the impacts of panels on lighting features inside the space. The reference model is experimented under different lighting conditions from direct sunlight (DS) of a clear sky to diffuse lighting of artificial skies (AS) with cool to extreme warm color temperatures. M/P-ratios of the interior space are accumulated between slightly above 0.85 to slightly above 0.9 under direct sun lighting (DS) with around 5000 K color temperature at the vertical surface. Interior CCTs are mostly distributed between 5000 and 5500 K under DS conditions. M/P-ratios of the scene are changed to slightly above 0.8 to about 0.95 under an artificial sky diffuse lighting with 5700 K color temperature (AS-1). Interior CCTs are distributed within 5000 K to 5500 K under such lighting conditions. M/P-ratio accumulations are between around 0.75 to 0.85 by applying the artificial sky diffuse lighting with 4400 K color temperature (AS-2). Under AS-2 lighting conditions, CCTs of the scene are between 4000 °K to 4500 °K. The distribution of M/P-ratios fluctuate from around 0.55 to slightly above 0.65 under the very warm diffuse lighting with 2800 K color (AS-3). The color temperature of the scene accumulates between 2500 K to 3000 K for AS-3 lighting conditions. The impacts of different SPs' variables on healthy lighting performance of the reference model are explained in the following sections.

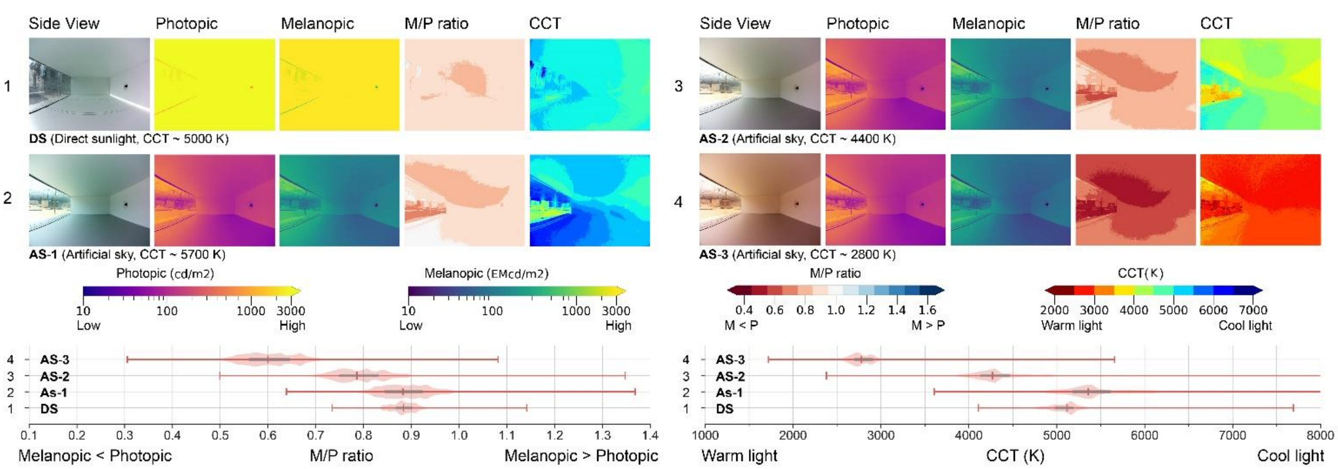


Figure 4. 8. Lighting performance of the reference model under different lighting conditions with various color temperatures.

4.6.2.1 Panels' color impacts on photobiological lighting

The results of lighting experiments show that panels with cool colors, including strong blue, light blue, strong green and cool white, increase melanopic units and the color temperature of light in the scene under all outdoor lighting conditions. As shown in the examples of false color maps in Figure 4.9, the M/P-ratio of cool color panels are increased towards higher melanopic units (higher M/P-ratio) and the corresponding CCTs are moved towards cooler lighting (higher color temperatures) compared to the reference cases under all outdoor lighting conditions (Figure 4.8). As shown in Figure 4.10-left column, the light blue panels considerably increase M/P-ratios, up to 15% in average, compared to the reference model. The light blue impacts are higher than the corresponding amount for strong blue-color panels. Strong green and cool white colors' impacts on M/P-ratios are slighter than strong and light blue colors. The M/P-ratio accumulation of strong green and cool white colors are moved slightly towards higher melanopic units compared to the reference model under all outdoor lighting conditions, e.g., see strong green and cool white M/P-ratios in row-c. Considering CCT distributions in Figure 4.10-right column, the strong and light blue colors panels significantly increase color temperature of light inside the space. The CCTs' distribution of light blue panels is increased by about 500 K to 3000 K compared to the corresponding ranges of the reference under very warm to cool diffuse outdoor lighting conditions. Strong blue color panels increase the CCTs' distribution by about 250 K to 2000 K compared to the reference under direct sunlight to cool and warm diffuse artificial sky lighting. Strong green also increases the CCT about 500 to 1000 K which is lower than the impacts of strong and light blue colors. Cool white color slightly increases the CCTs up to 500 K. The impacts of all cool color panels are considerably reduced when the outdoor lighting is very warm as shown in row-d.

On the contrary, warm color panels, including strong red, strong yellow, yellow green and warm white, increase photopic units and reduce the color temperature of lighting inside the space. As illustrated in the examples of false color maps in Figure 4.9, the M/P-ratios of warm color panels are moved towards higher photopic units (lower M/P-ratio) and the corresponding CCTs are distributed towards warmer lighting (lower color temperatures) compared to the reference model under all lighting conditions (Figure 4.8). Considering the M/P-ratio distribution plots in Figure 4.10-right column, panels with strong yellow and yellow-green colors have considerable impacts on increasing photopic units of the scene, up to 20%, compared to the reference model M/P-ratio distributions under direct and diffuse outdoor lighting conditions. Strong red color panels increase photopic units of the light, up to 10%, compared to the reference model under different outdoor lighting conditions. Strong yellow and yellow-green panels have slightly higher impacts than red-color panels. Warm white color panels contribute slightly to photopic units by reducing the accumulation of high M/P-ratios in the scene compared to the reference model. In terms of the CCT distribution in Figure 4.10-right column, the CCT accumulation of yellow color panels considerably decreases, up to 1000 K, under all lighting conditions compared to the reference model CCT accumulations. The yellow color panels have slight impacts on reducing CCTs under very warm diffuse lighting conditions (row-d). Strong red color panels decrease the color temperature of light inside the space from 500 K to 1000 K under all outdoor lighting conditions. The yellow-green color panels decrease the CCT accumulations of the scene up to 500 K which is slighter than the impacts of strong red and strong yellow under similar outdoor lighting conditions. The warm white color panels slightly move the CCT accumulation towards lower temperatures. The yellow-green and warm white colors panels' impacts on CCTs are considerably reduced under very warm lighting conditions (row-d).

Panels with different colors on each side, such as strong blue/red and light blue/strong yellow, increase melanopic units and the color temperature when the cool color is located on the top. On the contrary, such panels increase the photopic units and decrease color temperature when the warm color is located on the top. As illustrated in Figure 4.10, the M/P-ratio and CCT distributions are increased towards higher melanopic units and higher temperatures under different lighting conditions when the bluish colors are located on the top side of panels. On the contrary, the M/P-ratio accumulations are distributed towards higher photopic units and the CCT accumulations are moved towards warmer temperatures when the strong red and yellow colors are located on the top side of panels. The false color maps of different color-side panels, as some examples in Figure 4.9, show that the top-side color mostly affects lighting features on the ceiling whereas the bottom-side color has slight impacts on the floor. The impact of each side color is about 10% slighter than the impacts of using similar color on both sides. For example, the impacts of strong blue(top)/red(down) panels are slighter than the panels with strong blue on both sides. The behavior of multicolor panels is further discussed in the following by comparing horizontal and vertical orientations.

In all cases, a lighting color spectrum is generated in the scene similar to the panels' color. For example, blue color panels produce bluish light in the space as illustrated in Figure 4.9. Likewise, yellow color panels generate yellowish light, green panels produce greenish light and red panels create reddish light in the scene.

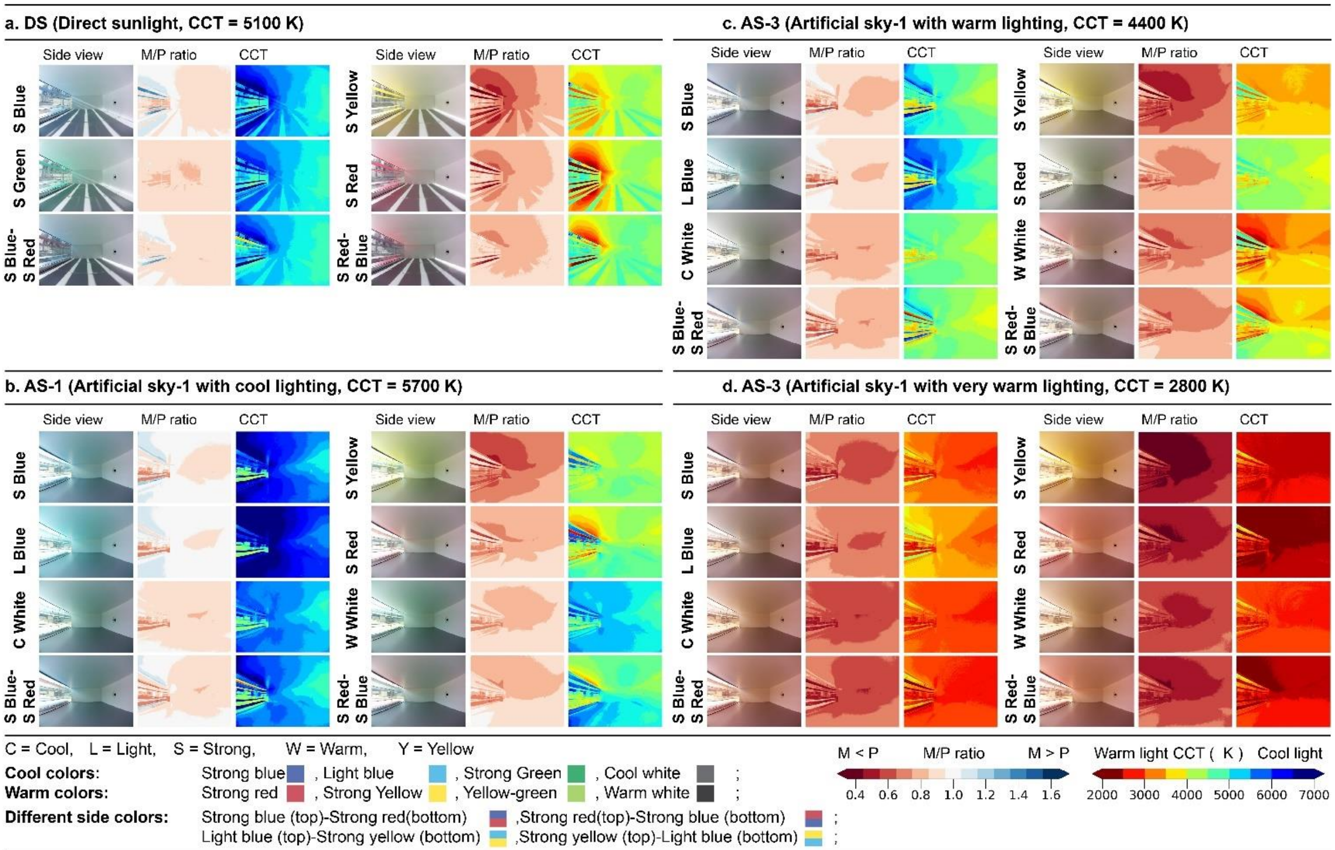


Figure 4. 9. Example of M/P-ratios' and CCTs' false color maps of different panels' colors under different exterior lighting conditions

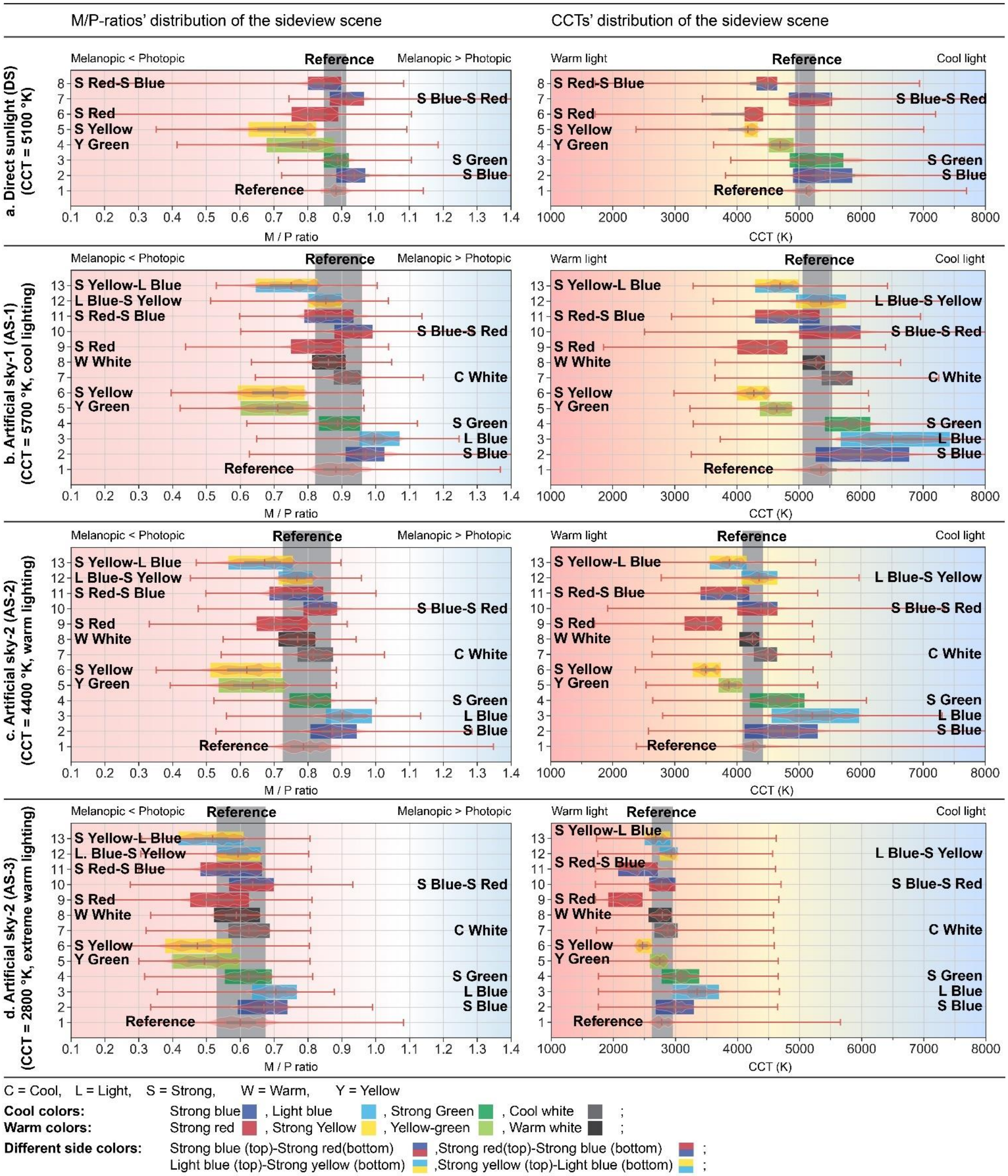


Figure 4. 10. Lighting performance of panels' colors under different lighting conditions.

4.6.2.2 Panels' reflectance impacts on photobiological lighting

The magnitude of matt color panels' impacts in the entire scene is higher than the similar colored panels' impacts with a glossy finish under different lighting conditions. The panels' reflectance impacts on lighting features are calculated for a similar color scheme in two reflectance levels including matt and glossy. False color maps, as some examples in Figure 4.11, show that the impacts of matt finish panels on M/P-ratios and CCTs are magnified all over the space compared to the glossy finish panels with similar cool or warm color schemes under direct sun lighting, cool and warm diffuse lighting conditions. For example, the impacts of the matt strong blue color panels on increasing melanopic units and CCTs of light is amplified all over the scene compared to the impacts of the glossy blue color panels. Likewise, the impacts of matt strong red color panels on increasing photopic units and decreasing CCTs of light are amplified compared to glossy strong red color panels.

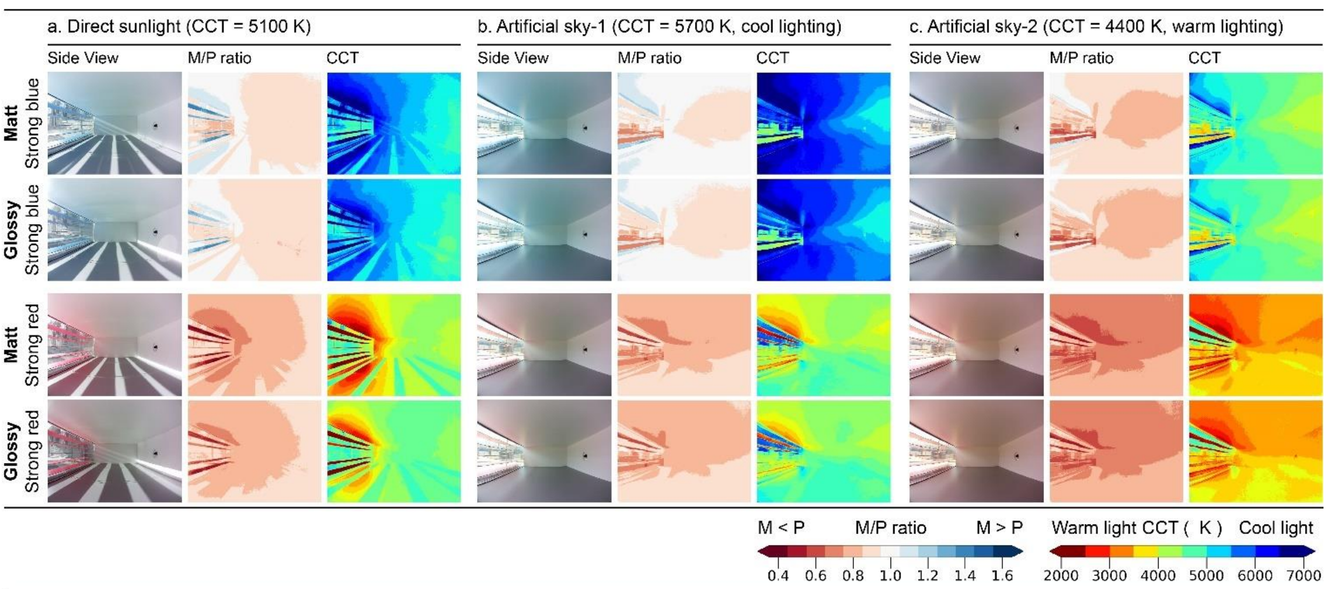


Figure 4. 11. Lighting performance of panels' reflectance under different lighting conditions

4.6.2.3 Panels' orientation impacts on photobiological lighting

Results of experiments show that panels' horizontal/vertical orientations direct impacts of side colors towards different viewpoints and surfaces in the space including ceiling and floor or left and right walls as some examples illustrated in Figure 4.12. The horizontal orientation directs the impacts of panels' colors, particularly the color on the top side in the case of multicolor panels, towards the ceiling of the space. The horizontal panels' impact on the right-side wall is similar to the left-side which is independent of the point of view from either the left or right side of the scene. The vertical orientation directs the impacts of panels' colors to the left- and right-side walls of the space.

Multicolored vertical panels' impacts depend on the individual's viewpoint in the space towards the particular side of the panels. The horizontal orientation also slightly increases the magnitude and depth of panels' colors impacts within the space compared to the vertical orientation of panels with similar surface features. Back view scenes and false color maps of some cases are illustrated in Figure 4.12 to clarify different orientations' behaviors. As illustrated in violin plots, the overall magnitude and depth of single-color horizontal panels' impacts, e.g., the strong blue case, are slightly higher compared to the vertical panels with a similar color. The false color maps of horizontal panels show the higher impacts on M/P-ratios and CCTs of the ceiling compared to the vertical panels.

Considering the multicolored horizontal panels' false color maps in Figure 4.12, e.g., strong red on the top side and strong blue on the bottom side, the M/P-ratio and CCT of the ceiling are decreased due to the impacts of strong red color (top-side color) which is almost similar to, yet with a lower magnitude, the pattern of panels with strong red color on both sides. The M/P-ratio and CCT of the floor is, however, increased in the case of strong red -strong blue panels because of the impacts of the strong blue color on the bottom-side. On the contrary, the panels with strong red color on both sides decreased the M/P-ratio and CCT of the floor. Considering back-view false color maps, the multicolored horizontal panels' impacts on M/P-ratios and CCTs of the right-side wall are similar to the left-side. The overall impact of the panels' top-side color, strong red, is dominated in the view as reddish light appears in the scene. Therefore, multicolored horizontal panels impacts are independent of viewpoints in the space.

The impact of multicolored vertical panels on the M/P-ratio and CCT of light in the space depends on the viewpoint towards the particular side-color. As illustrated in the back-view false color maps of strong blue (left side)-strong red (right side) vertical panels in Figure 4.12, the patterns of M/P-ratios and CCTs on the right-side wall is different from the corresponding patterns on the left-side wall. The right-side wall is influenced by the red color resulting in the decrease of M/P-ratios and CCTs, whereas the left-side wall is affected by the blue color resulting in the increase of the M/P-ratios and CCTs. Reddish light is generated on the right-side wall because of the panels' red color side impacts whereas bluish light is produced on the left-side wall due to the impacts of panels' blue color side. Therefore, the impacts of multicolored vertical panels depend on the individual's viewpoint towards the particular color of the panels' side in the field of view.

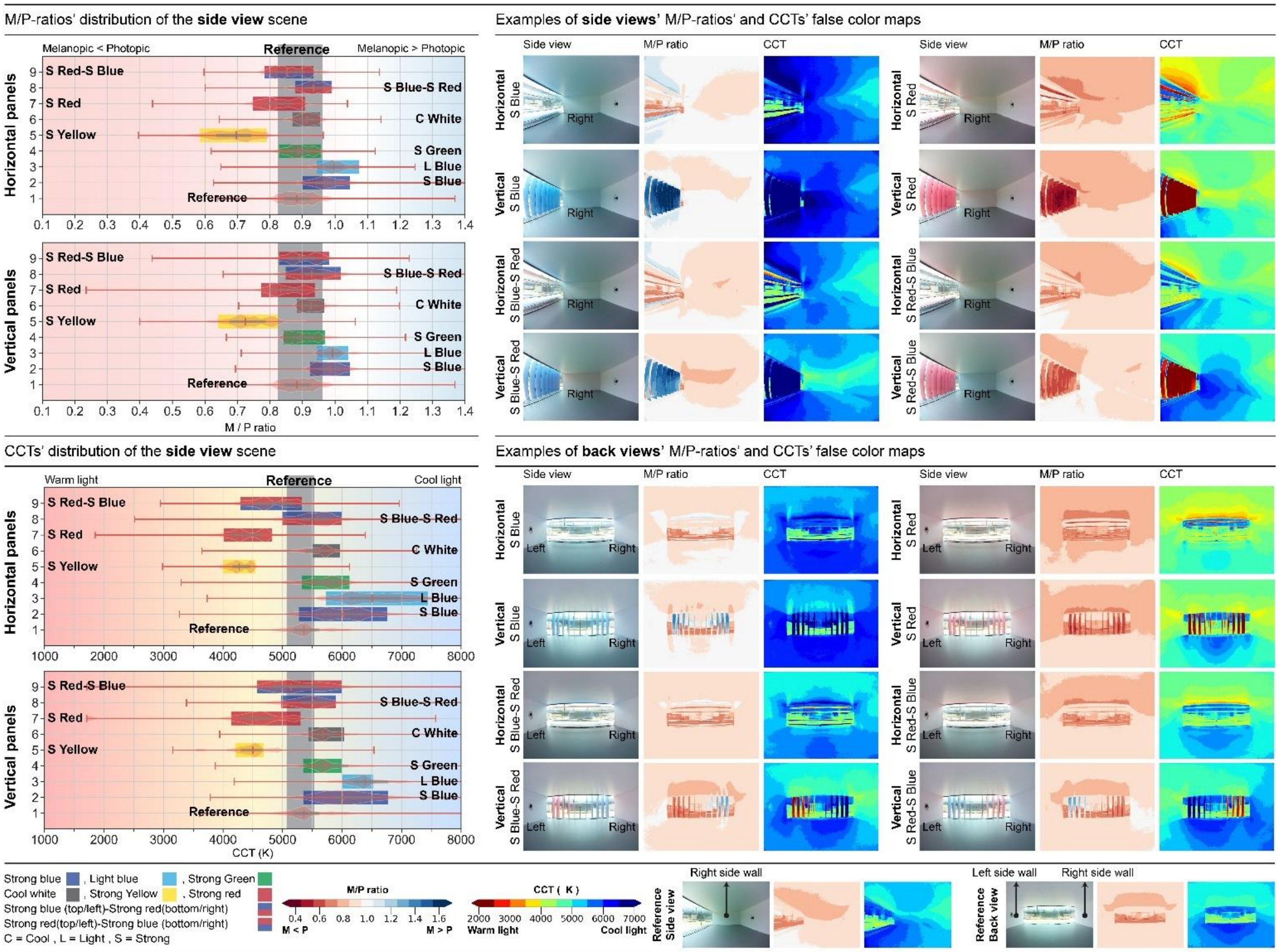


Figure 4. 12. Lighting performance of panels' orientation, vertical vs. horizontal under the diffuse artificial sky lighting condition (CCT= 5700 °K)

4.6.2.4 Panels' inclination impacts on photobiological lighting

The impacts of panels' color titled up are significantly amplified compared to the horizontal (zero-degree inclination) or titled down panels with a similar color under diffuse lighting conditions. The impacts of panels' color titled down are considerably reduced compared to the horizontal panels under all diffuse outdoor lighting conditions from cool to extreme color temperatures. As some examples depicted in Figure 4.13, the strong blue color panels have considerably higher impacts on increasing M/P-ratios and CCTs of light all over the space compared to the horizontal and tilted down panels. The blue color panels titled down have considerably slighter impacts on M/P-ratios and CCTs over the space compared to horizontal panels. In the case of multicolored panels, the impacts of top-side color are amplified under the upward inclination whereas the impacts of the bottom-side color are magnified under the downwards inclinations.

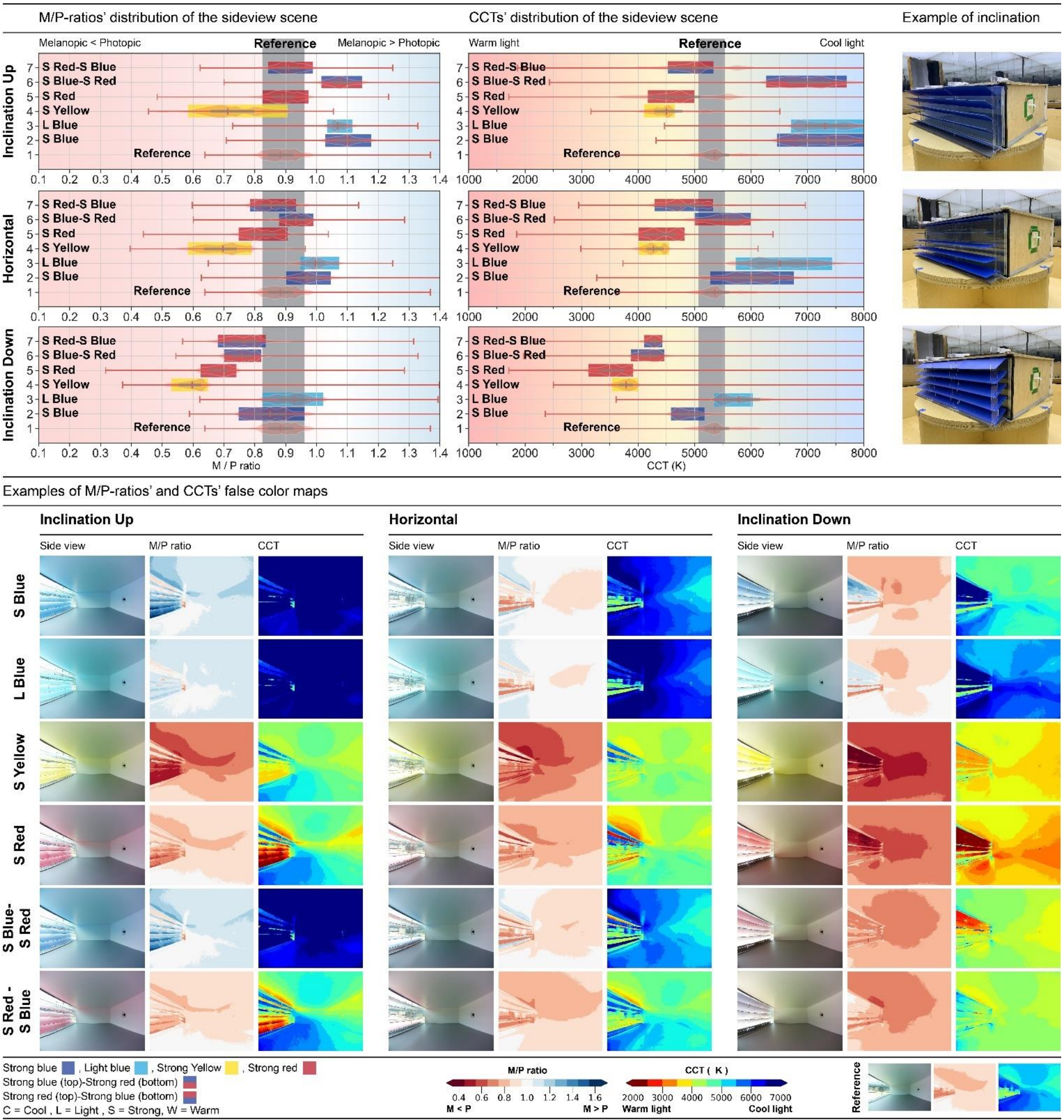


Figure 4. 13. Lighting performance of panels' horizontal inclinations under the diffuse artificial sky lighting condition (CCT= 5700 °K)

The impacts of panels inclined to left are considerably higher than the similar color vertical panels with zero inclination to left or right under different outdoor lighting conditions. As some examples depicted in Figure 4.14, the blue color panels tilted left have higher impacts on M/P-ratios and CCTs of the scene compared to the blue color vertical panels with no inclination towards left or right. In the case of multicolored panels, the impacts of the color on the inner side are magnified within all viewpoints in the space. That means, for example, the impacts of the blue color on the left-side are further expanded to all views from the left-side wall to the right side compared to the impacts of multicolored vertical panels which are depending on the viewpoint in the space.

Folded vertical panels, as a V-shape displayed in Figure 4.14, slightly decreases the magnitude of panels' color impacts compared to the vertical panels of a similar color because the openness between panels is increased under the V-shape configuration. The impacts of openness are discussed in the following. In the case of multicolored folded panels, the inner-side color has major impacts on lighting features in the space. For example, in the case with the blue color inside and the red color outside as shown in Figure 4.14, the blue color of the inner side increases the M/P-ratio and CCT of light in the space. On the contrary, in the case with the red color inside and blue color outside, the red color of the inner side decreases the M/P ratios and CCT of the scene. Such behaviors can be seen in the side and back views. Therefore, the multicolored V-shape panels' impacts are independent of the viewpoint in the space.

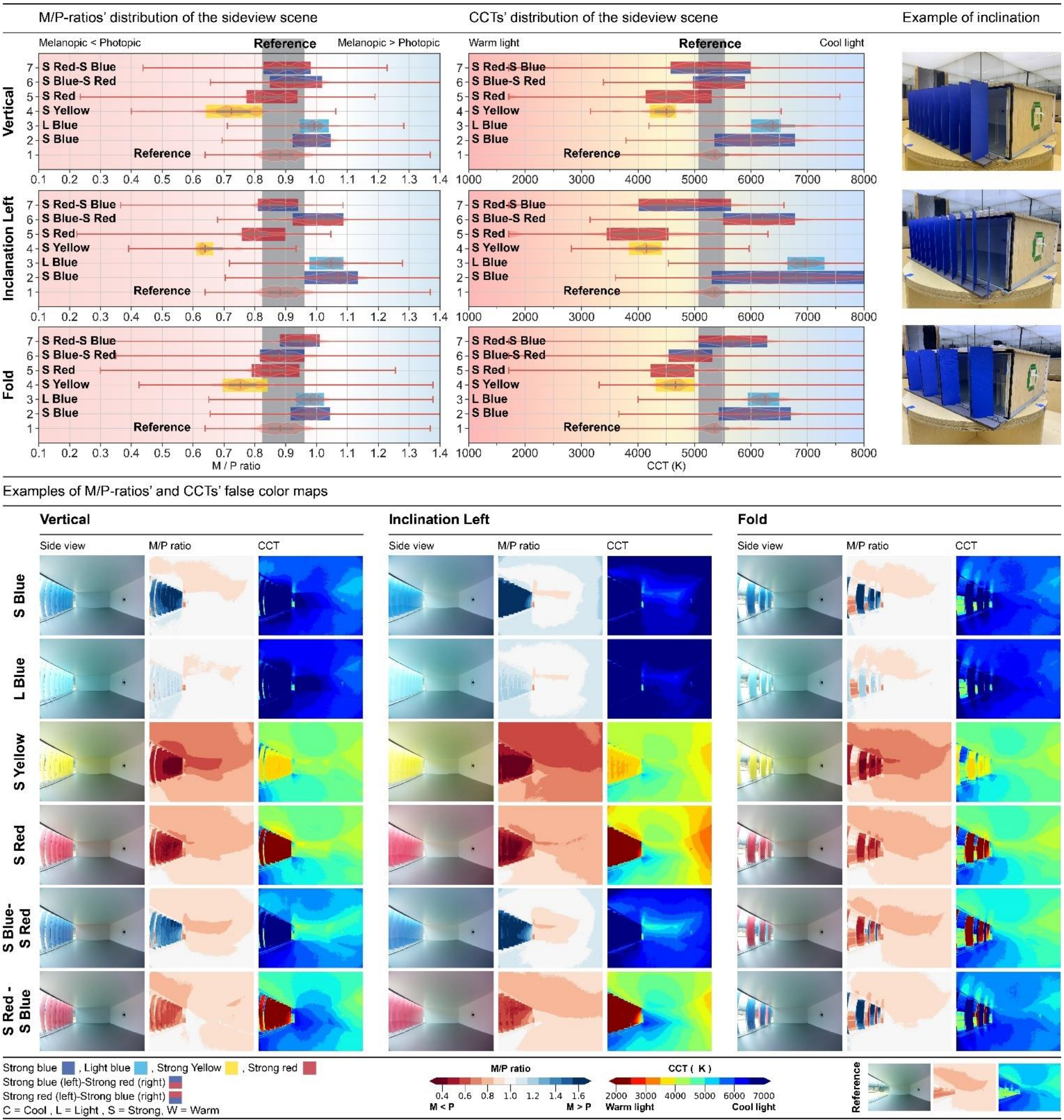


Figure 4. 14. Lighting performance of panels' vertical inclinations under the diffuse artificial sky lighting condition (CCT= 5700 °K)

4.6.2.5 Panels' density/size/position impacts on photobiological lighting

Reducing the panels' density, for example from 5-row to 3-row panels as shown in Figure 4.15, slightly decreases the magnitude of colors' impacts on lighting features in the space under different diffuse lighting conditions. The M/P-ratio and CCT of the lower-density panels are slightly decreased compared to the corresponding distributions for high-density panels (Figure 4.15). Sharply reducing the panels' size slightly decreased the magnitude of panels' impacts on lighting features. As can be seen in false color maps of some examples in Figure 4.15, the impacts of blue color panels with size (ii) or (iii) on the M/P-ratio and CCT of light are lower than the bluish panels' size (base) or (i) which are about two and three times bigger than the former sizes. The small size panels still have noticeable impacts on the M/P-ratio and CCT of the scene. The panels' colors with any size have considerable impacts on the lighting temperature in the scene.

Positioning the panels at the top of the opening with an upward inclination affects lighting features inside the space under diffuse lighting conditions, which is higher than the impacts of the top-positioned horizontal panels, as shown in Figure 4.15. Panels with a downward inclination positioned at the top decrease the outdoor lighting penetration in the space. The impacts of panels' color with a downward inclination positioned at the top decreased in the space, especially on the ceiling, as such panels' configurations reduce the outdoor lighting penetration in the space. Positioning the panels at the bottom of the opening with horizontal or upwards inclinations considerably increases the magnitude of color impacts on lighting features in the scene under different diffuse lighting conditions. As illustrated in Figure 4.15, bluish upwards panels positioned at the bottom have significant impacts on the M/P-ratio and CCT of light. The impacts of bluish horizontal panels at the bottom on increasing the M/P-ratio and CCT, are slighter than the similar panels with an upwards inclination.

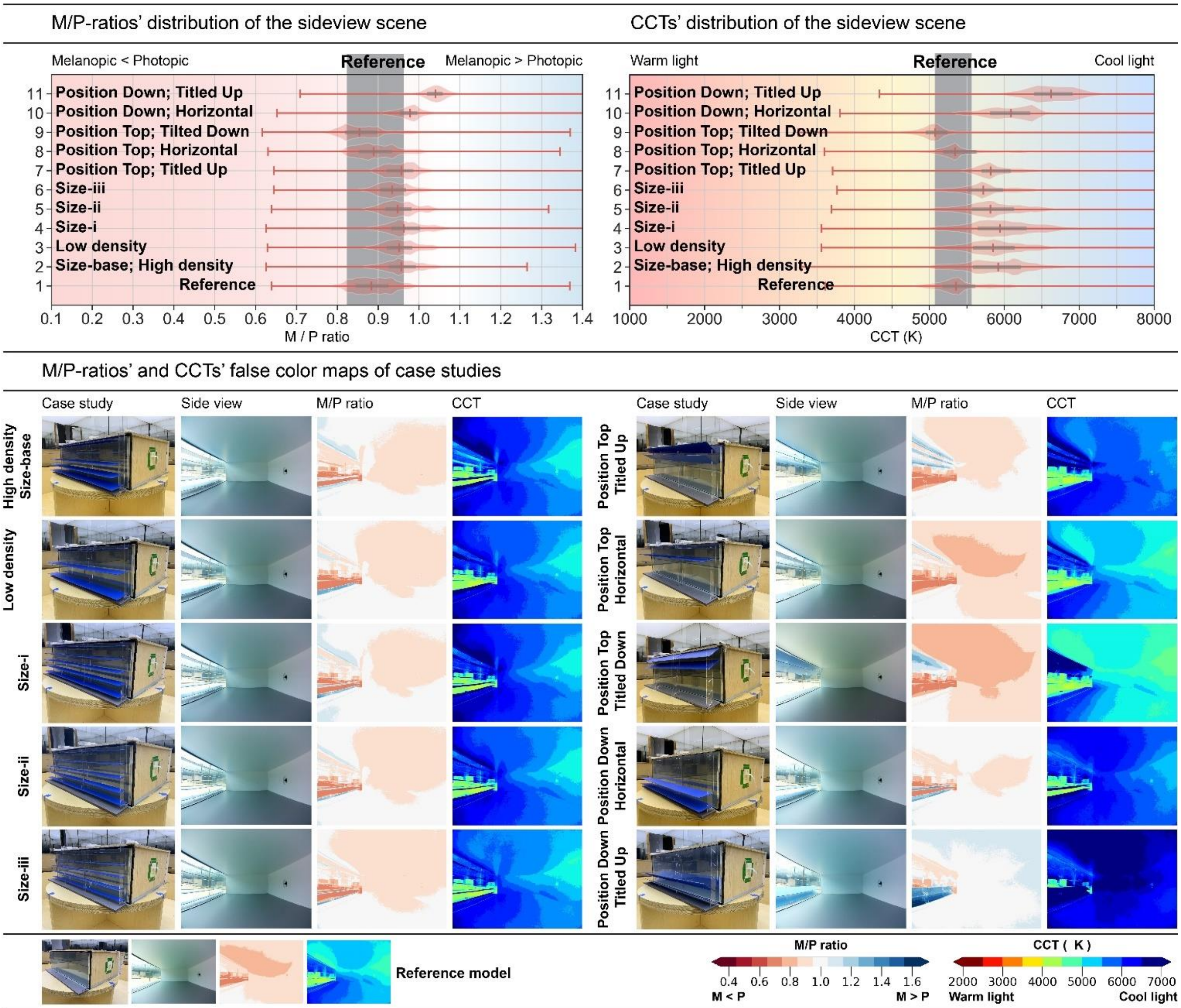


Figure 4. 15. Lighting performance of panels' density, size, and position under the diffuse artificial sky lighting condition (CCT= 5700 °K)

4.6.2.6 Adjusting panels' configuration to lighting adaptation scenarios

Synthesizing the experimental results for Northern buildings suggests using horizontal multi-colored (i.e. two or more colors) matt panels with a dynamic behavior for upwards/downwards inclinations and movements in relation to hourly photobiological lighting requirements. For example, a potential different colored-sides panel configuration is proposed in Figure 4.16-a to address hourly/seasonal photobiological needs of occupants in the case study of an office in Kuujjuaq, Quebec, (Northern) Canada, developed based on Parsaee, et al. [263], [283]. Horizontal matt panels with light-bluish and cool-whitish colors could apply from 7:00 to 13:00 to potentially stimulate positive photobiological responses in terms of synchronizing individuals' body clocks and increasing alertness, and visual performance. Horizontal matt panels with strong-yellowish and strong-reddish colors are proposed from 15:00 to 19:00 to potentially stimulate positive photobiological responses in terms of adjusting individuals' body clocks and alertness for the nighttime combined with a proper visual performance. Figure 4.16 shows efficient photobiological arrangements of panels' colors which, for example, imply potential rotation or flip of square panels with different colors from the morning to evenings. From the proposed four colors in the graph, a set of a cool and a warm color for different sides of square panels could enable potential photobiological daylighting adaptation in Northern latitudes. Figure 4.16specifically shows adaptations of panels with light-blue and strong-yellow for typical Northern summer and winter days. High-density panels over the window could be used under high-intensity Northern daylighting. Low-density panels positioned at the bottom of the window could be used under low-intensity overcast Northern daylighting. Upwards/downwards inclinations of horizontal panels could offer more effective modifications of healthy daylighting parameters under low-altitude Northern sun lighting. LED lighting systems could be used during the short winter days when a few hours of daylighting are available. Panels could cover the office openings from 19:00 to 7:00 (Figure 4.16-a and b) as unoccupied times of weekdays and 24 hours of weekends throughout the year to prevent potential heat losses, the diffusion of indoor artificial lighting to outdoors and penetration of summer evening daylighting.

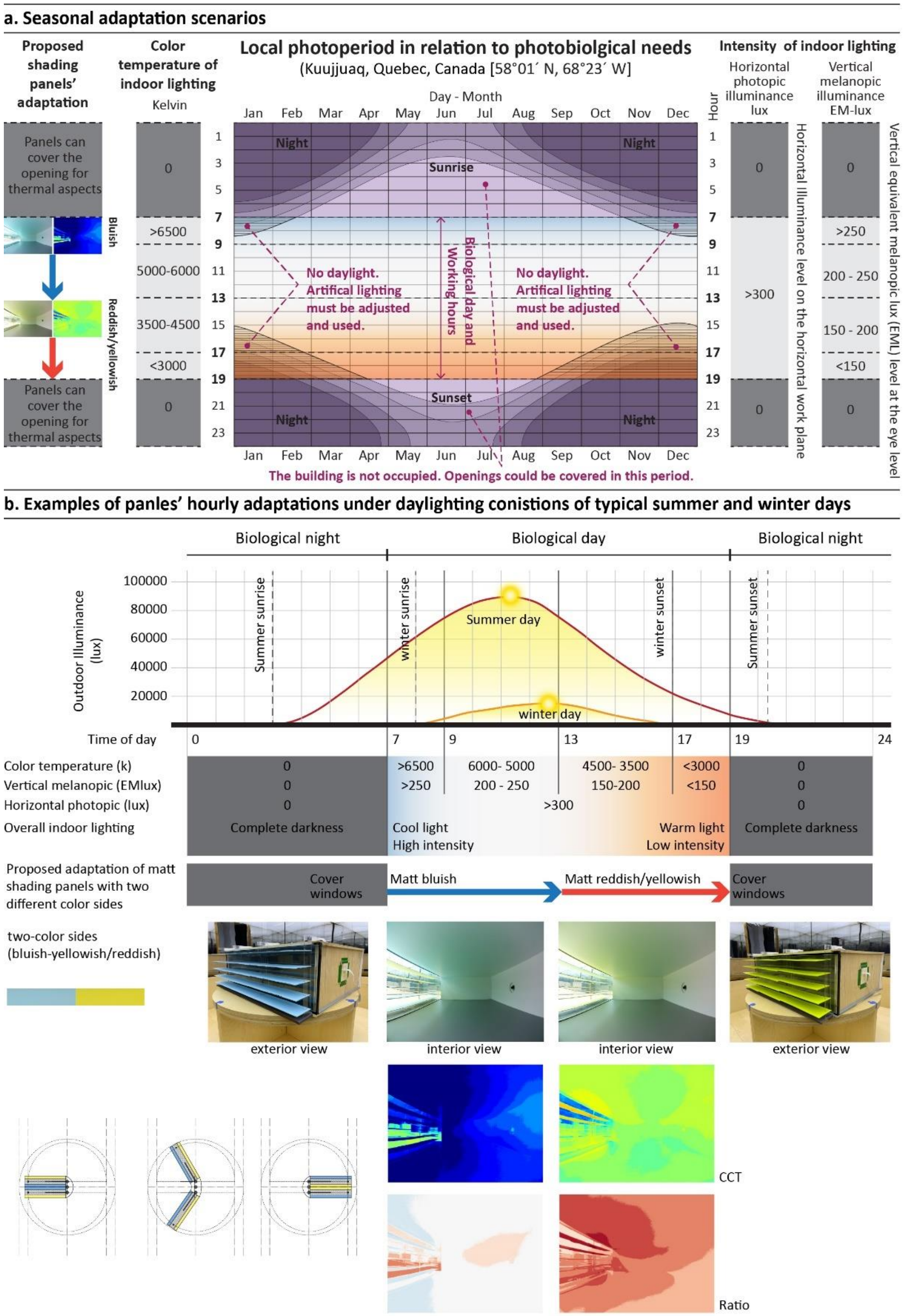


Figure 4. 16. (a) adaptation of dynamic insulated panels with different colors to the local photoperiod and occupants' seasonal photobiological needs in the reference office, considered Kuujjuaq, QC, CA, as an example location, based on [263], Parsaee, et al. [283], (b) examples of hourly adaptations of different colored panels under a typical Northern summer day with clear skies (15 June) and Northern winter day with overcast skies (20 January) (typical days were extracted from the typical meteorological year (TMY)).

4.7 Conclusions

This paper developed a fundamental model of biophilic-photobiological adaptive envelopes for sub-Arctic buildings which could address occupants' photobiological -psychological wellbeing in harsh sub-Arctic climates compared to conventional façades recommended by Canada building codes. The main elements of the proposed adaptive model include optimum window sizes, dynamic-colored-insulated shading panels and a thermal buffer system as intermediate spaces. This paper is focused on studying biophilic and photobiological impacts of sub-Arctic envelopes. The results indicated that window sizes around 60% WWR offer efficient biophilic connections with the outdoor sub-Arctic nature in contrast to the Canada building codes' recommendations of 20% WWR. Multi-colored dynamic-insulated panels are shown that could adapt Northern daylighting conditions to occupants' photobiological needs which has not yet been considered in Northern Canadian buildings. Comprehensive evaluations of panels' characteristic impacts on photobiological parameters are studied which include the performance of different colors from cool bluish to warm reddish, reference from glossy to matt, horizontal/vertical orientations, upwards/downwards inclinations, tilted left/right, small to large sizes, low to high densities and top/bottom positions at the window. The evaluations suggested employing multi-colored sides panels, e.g., two-colored sides with cool and warm colors such as bluish and yellowish, with abilities to rotate, flip, or move, could adapt daylighting parameters to hourly photobiological needs of occupants in the space. As a potential challenge, higher WWRs increases building heat losses and energy consumptions of heating systems. Regarding this issue, the research provides an *overview* in the appendix that integrating dynamic-colored-insulated panels and intermediate spaces to the envelope could act as a thermal buffer system and improve thermal/energy efficiencies. Overall, the paper outlines the following issues for future developments.

- The proposed envelope could enable positive efficient relationships among Northern occupants and the harsh outdoor nature. Considering biophilic indicators, optimum window sizes of around 60% WWR offer efficient direct connections with the outdoor nature which could stimulate different visual/non-visual biological responses and perceptual/cognitive phenomena. The adaptive configuration of the proposed envelope with dynamic panels also enables controllable sequential connections with outdoors which could control occupants' exposure to different desirable/undesirable sub-Arctic natural phenomena.
- The proposed envelope with dynamic-colored-insulated panels could address hourly/seasonal photobiological needs of occupants in relation to Northern daylighting

conditions. The color, reflectance, orientation, inclination, density, and position of panels could adjust healthy daylighting parameters, i.e., photopic and melanopic units and color temperature, under different direct and diffuse Northern daylighting conditions.

- *As the focus of this paper is directed towards biophilia and photobiology*, future research must study thermal performance of the proposed biophilic-photobiological envelope system with the efficient WWR of around 60%, dynamic-colored-insulated panels and intermediate spaces, especially in terms of using advanced materials with high thermal efficiency properties and abilities of thermal mass and heat storages which could improve overall thermal and energy efficiency. Resilience and robustness of the envelope components and materials and potential risks of condensation and freezing on the exterior skin must be also studied. Adjusting indoor artificial lighting, especially LED lighting, with the proposed envelope performance to address occupants' photobiological needs during dark winter daytimes must be further studied.

4.8 Acknowledgment

This research was supported by the Sentinel North program of Université Laval, made possible, in part, thanks to funding from the Canada First Research Excellence Fund.

4.9 Supplementary Information

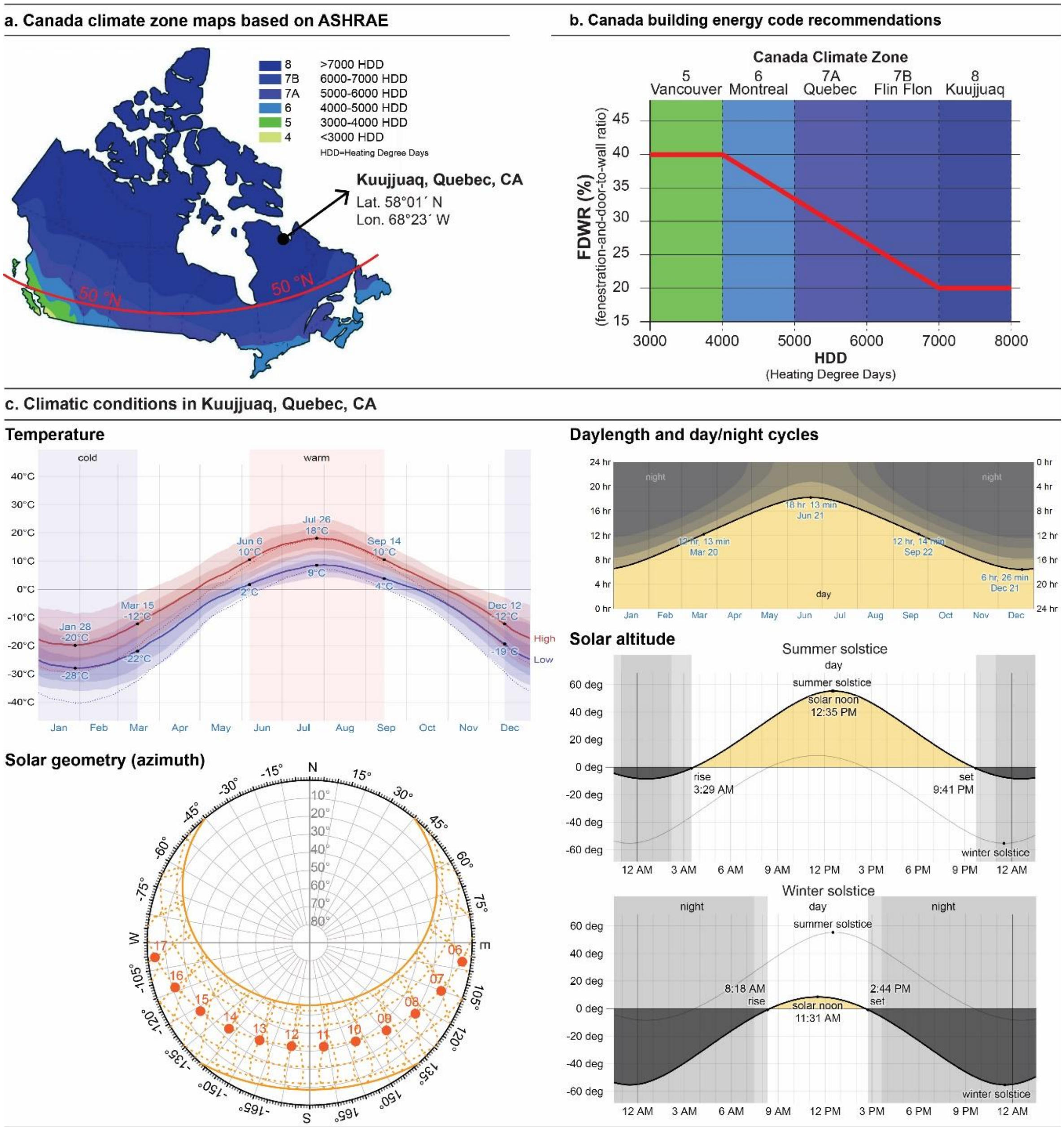


Figure 4 | Supplementary 1. (a) Canada climate zone maps (retrieved from Straube [137]) (b) Recommendation of National Energy Code of Canada for Buildings (NECB) for the fenestration-and-door-to-wall ratio (FDWR) in different climate zones of Canada as the given example cities (retrieved from ASHRAE [30], NRC [136], Straube [137]), and (c) climatic conditions in Kuujjuaq, QC, CA (retrieved from Weather spark [46], Marsh [311])

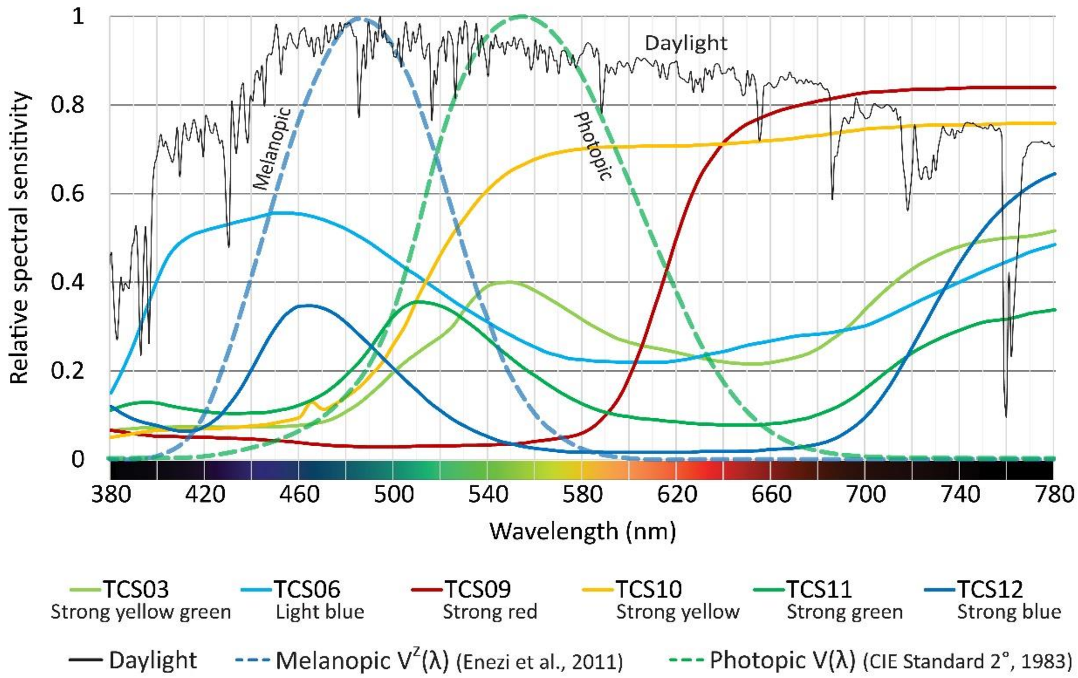


Figure 4 | Supplementary 2. Relative spectral sensitivity of different test color samples (TCS) published by Waveform Lighting [309], D55 daylight illuminant (retrieved from DiLaura, et al. [13], ASTM G173-03 [64]), and melanopic efficacy (retrieved from Enezi, et al. [66], Amundadottir, et al. [68]) and photopic efficacy (retrieved from DiLaura, et al. [13], CIE [312]) curves

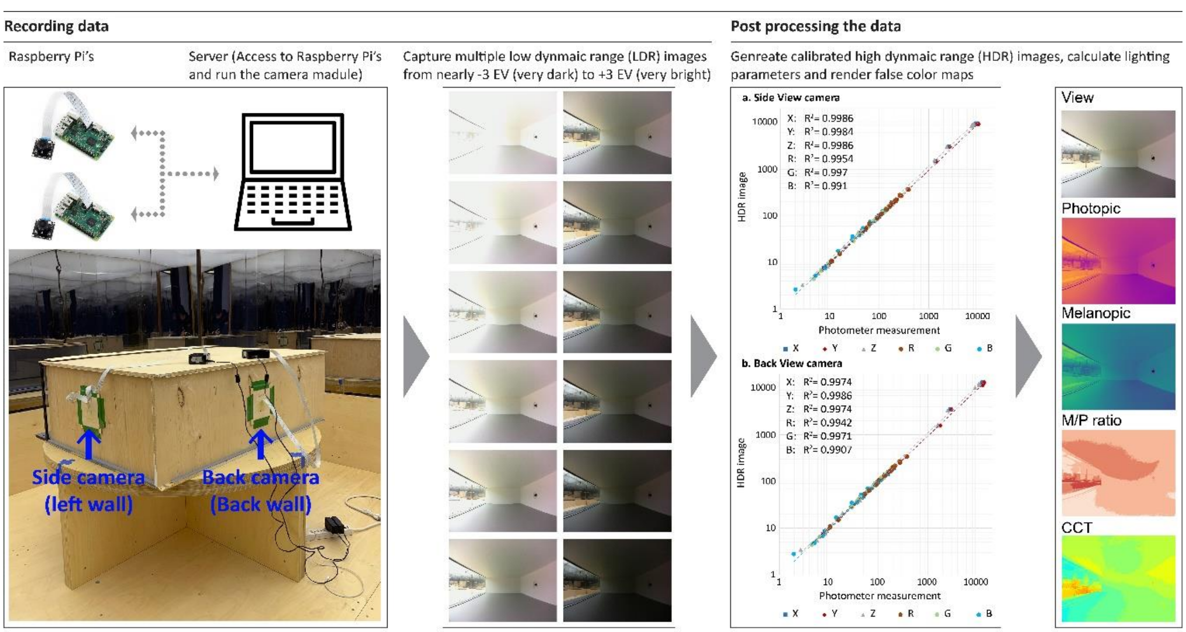


Figure 4 | Supplementary 3. HDR imagery and post processing of lighting performance inside the scale model under direct sun lighting and artificial skies diffuse lighting

Table 4 | Supplementary 1. Characteristics of typical materials used in the model determined by [313, 314]

Material	Specularity value (SV, %)	Lighting reflectance value (LRV, %)	Visual transmittance (VT, %)	R	G	B
Strong blue		5-10		1	80	134
Light blue		50-65		162	213	231
Strong green		25		1	157	110
Yellow Green		48		178	194	22
Strong yellow		60-75		254	217	93
Strong red		10-15		191	45	50
Cool white		90-95		247	247	241
Warm white		85-90		246	242	232
Light gray		25-35		149	155	160
High glossy vanished	40-60					
Glossy varnished	20-30					
Matt varnished	0-5					
Double glazing window			70-80			

Table 4 | Supplementary 2. The experiment scenarios to evaluate the lighting performance of panels' design variables under different exterior lighting conditions

Configuration		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9
Exterior lighting condition	DS	●	●							
	AS-1			variable	variable	variable	variable	variable	variable	variable
	AS-2			variable	variable	variable	variable	variable	variable	variable
	AS-3			variable	variable	variable	variable	variable	variable	variable
Color	S blue	variable	variable	variable	variable	variable	variable	●	●	●
	L blue			variable	variable	variable	variable			
	S green	variable	variable	variable	variable	variable	variable			
	Y green	variable	variable	variable	variable	variable	variable			
	S yellow	variable	variable	variable	variable	variable	variable			
	S red	variable	variable	variable	variable	variable	variable			
	C white			variable	variable	variable	variable			
	W white			variable	variable	variable	variable			
	S blue-S red	variable	variable	variable	variable	variable	variable			
	L blue-S yellow			variable	variable	variable	variable			
Reflectance	Matt	variable	variable	variable	variable	●	●	●	●	●
	Glossy	variable	variable	variable	variable					
Orientation and Inclination	Horizontal (0°)	●		●		variable		●	●	variable
	Vertical (0°)		●		●		variable			
	Up (+30°)					variable				variable
	Down (-30°)					variable				variable
	Left (+30°)						variable			
	Fold - V shape						variable			
Density	High density	●	●	●	●	●	●	variable	●	
	Low density							variable		●
Size	Size - Base	●	●	●	●	●	●	●	variable	●
	Size-i								variable	
	Size-ii								variable	
	Size-iii								variable	
Position	Entire window	●	●	●	●	●	●	●	●	variable
	Top position									variable
	Bottom position									variable
DS: direct sun lighting; AS: artificial sky lighting; S : strong; L: light; Y: yellow; C: cool; W:warm										

4.10 Appendix 4.A

An overview towards thermal and energy performance of the proposed biophilic-photobiological envelope model

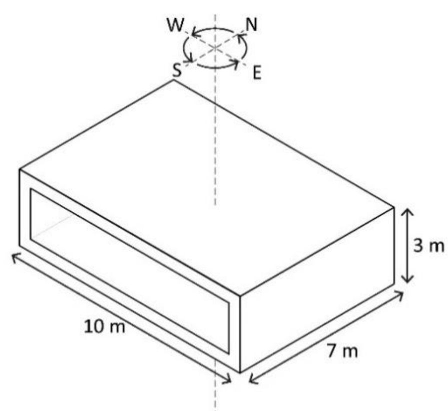
This research proposed developing intermediate spaces for the biophilic-photobiological adaptive envelope model as a promising solution which could improve thermal and energy performance by creating a thermal buffer among interior surfaces and exteriors. To show the efficiency of such thermal buffer systems, a simplified thermal model of the reference office is developed to compare the thermal/energy performance of the proposed envelope system with the conventional Northern Canadian building façades. *As the research is focussed on biophilia and photobiology, the thermal model is designed to evaluate overall impacts of windows modifications and intermediate spaces on thermal/energy performance of the reference office A complex thermal modeling of the intermediate spaces as well as potential abilities of advanced materials or heat stages requires further studies in* *future research yet based on the efficient biophilic-photobiological envelope configurations proposed in this research.*

The numerical thermal model was developed with Energy Plus through IES Virtual Environment[314] to evaluate the thermal and energy performance of the proposed envelope for the reference open-space office in Kuujjuaq, QC, CA. The configuration of the numerical model is displayed in **Table 4 | A.1** validated based on the recommendations offered by National Building Code of Canada (NBC)[271], National Energy Code of Canada for Building (NECB)[136], the guide to building practices for Nunavik, Quebec, Canada[272], and ASHRAE [30], [121]. The numerical model computed the thermal energy corresponding to heating loads which are required to provide thermal comfort and healthy indoor air quality in the office directed towards the north, east, south, and west. The research, first, studied thermal energy performance of the office with a conventional façade and different WWRs, from 20% to 100%, to realize the effectiveness of the proposed thermal buffer. Next, the research evaluated the impacts of the proposed envelope configuration with the thermal buffer on energy performance of the reference office with 60%-WWR, as identified for efficient biophilic performance. Thermal impacts of the envelope were evaluated for a single glazing exterior skin with different intermediate depths combined with 20 cm dynamic-insulated panels, as the worst-case scenario, scheduled to cover openings from exteriors during weekdays' unoccupied hours and 24 hours of weekends. More specifically, the office was scheduled to be fully occupied from 8:00 to 18:00 for five days per week throughout the year. The heating system was set to run with a setpoint of 21°C from 6:00 until 18:00. The heating setback was set to 18°C from 18:00 to 6:00. The opening setpoint for natural ventilation in the intermediate space/cavity was set to 20°C of the outdoor temperature. Cooling demands were assumed to be addressed by natural ventilation under a free-run mode as Kuujjuaq has an extreme cold climate of sub-Arctic (**Figure 4 | Supplementary.1**). The climatic weather conditions were set to the typical meteorological year of Kuujjuaq published by [315]. A single façade of the model by the size of 7 m*3 m is designed with an opening and the other façades were considered to be opaque walls. The size of the thermal buffer and the depth of the intermediate space between the glazing skin and the interior skin/window are the main parameters modifying thermal performance. The hypothesized four fundamental configurations of intermediate spaces are, therefore, evaluated including a (i) window-size cavity, (ii) façade-size cavity, (iii) façade-size transient intermediate space similar to covered corridors, and (iv) façade-size habitable intermediate space similar to covered balconies/porches. To this end, the cavity/intermediate space was changed from a 20cm-depth-window-size cavity to a 200-cm-depth habitable intermediate space (as illustrated with results). All the exterior wall and roof surfaces of the cavities and intermediate are considered to be made of a single glazing window which has a high U-value and transmittance as well as a high infiltration rate, as the worst-case scenario (**Table 4 | A.1**). For all cases with the conventional façade and the proposed adaptive envelope, The window of the interior spaces is considered to be a typical low-e double glazing as recommended by National Building Code of Canada (NBC)[271], National Energy Code of Canada for Building (NECB)[136]. In brief, two general thermal evaluation scenarios were to address the research hypotheses include:

1. Thermal impacts of WWR variations from 20% to 100% for a conventional-façade office under different directions
2. Thermal impacts of the proposed envelope with different depths of the cavity and intermediate space combined with 20-cm insulated panels for an office with 60% WWR. The panels are scheduled to be open from 8:00 to 18:00 during five weekdays. The panels are closed from 18:00 to 8:00 during five weekdays and 24 hours of weekends. In the case of the transient/habitable intermediate space, the bottom surface, floor, is considered to be an opaque surface. Due to limitation of the software, the panels were considered to be horizontal over the window, as the open mode, during the working period.

Table 4 | A. 1. Configurations of the office thermal model

Office dimensions



R-value (efficient) of the opaque wall	3.85 (m^2K/W)
Roof and floor R-value (efficient)	5.03 (m^2K/W)
Double glazing window net U-value (including frame) applied to the exterior skin of cavity/intermediate space filled with Krypton	1.41 (m^2K/W)
Double glazing window, Outer pane transmittance	0.4
Double glazing window, Inner pane transmittance	0.78
Double glazing window SHGC	0.3856
Single glazing window net U-value (including frame) applied to the exterior skin of cavity/intermediate space	5.81 (m^2K/W)

Single glazing window visible light normal transmittance	0.78
Single glazing window SHGC	0.8116
Crack flow co-efficient for the single glazing window	0.15 (l/s/m/Pa^0.6)
Insulated panels R-value	2 (m^2K/W)
Heating set-point	21 °C
Heating set-back	18 °C
Opening setpoint for natural ventilation	21 °C (outdoor air temperature)
Office occupancy hours	08:00 - 18:00 of weekdays throughout the year
Occupancy density	14 (m^2/person)
People (latent and sensible heat)	150 (W/person)
Lighting	12.00 (W/m^2)
Computer and equipment	12.00 (W/m^2)
Infiltration rate of the interior space	0.35 ($l/s/m^2$)
Infiltration rate of the cavity/intermediate space	0.7 ($l/s/m^2$)
Auxiliary ventilation	8.5 (l/s/person)

The thermal analysis revealed that the proposed envelope improved thermal performance of the reference office with 60%-WWR under all directions in Kuujjuaq resulted in considerable decreases in heating loads. As illustrated in Figure 4 | A.1 for the office with a conventional façade, increasing WWRs of the north, east or west façade from 20% to 100% elevates heating loads up to 60 kWh/m^2/yr. Increasing the WWR of the conventional façade directed towards the south slightly increases heating loads, about 10 kWh/m^2/yr, because the high WWR under enables higher solar heat gains. The heating load of the conventional-façade office with 60%-WWR is almost twice the case with 20%-WWR under all directions. Heating loads of the office with 60%-WWR equipped with the proposed envelope configuration are considerably lower, up to 40 kWh/m^2/yr, than corresponding loads for the similar office with a conventional façade under different directions. Heating loads of the office with 60%-WWR and the proposed envelope are also lower than heating loads of the conventional-façade office with 20% WWR, especially under the south direction. The results indicated that the intermediate depth variation, from 20 to 200 cm, has slight impacts on the positive thermal performance of the proposed envelope. Considering biophilic benefits, using habitable or transient intermediate spaces are, thus, recommended.

The proposed envelope offers higher natural ventilation potentials in the reference office under the extreme cold weather of Northern Canada. The thermal analysis in Figure 4 | A.2 shows that the air temperature inside the cavity/intermediate space is warmer, up to nearly 10°C, than the outdoor air temperature during the cold winter days, about 7-8 months, in Kuujjuaq. The warmer in-between air could flow inside buildings to improve natural ventilation and indoor air quality. Considering biophilia, the warmer in-between space potentially encourages occupants to spend ample time inside such transient/habitable spaces. During summer days, the proposed glazing skin could be open to the desirable weather conditions to maximize the direct natural ventilation and connections with non-visual phenomena. Due to extreme cold sub-Arctic weather, there is no risk of overheating air/surface temperature inside such openable intermediate spaces during the summer (Figure 4 | A.2).

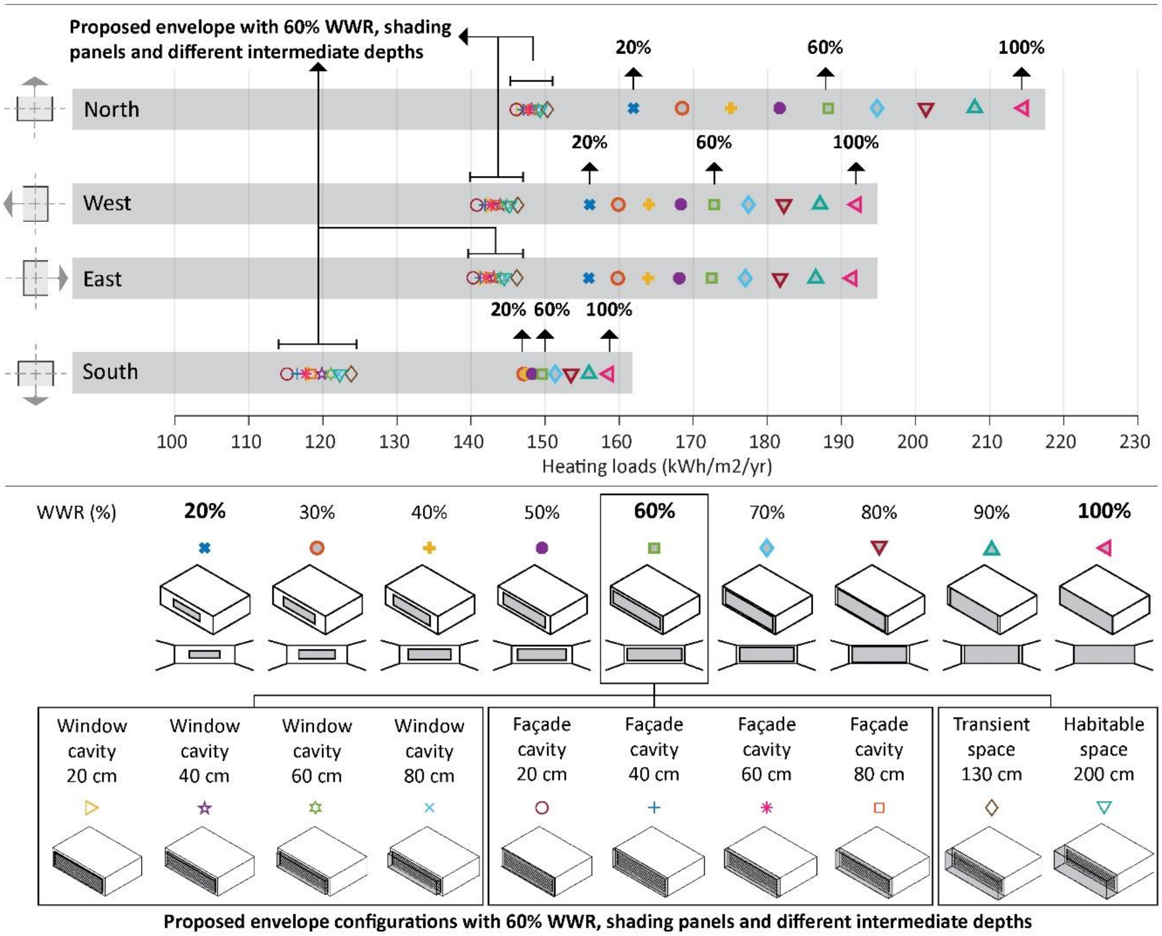


Figure 4 | A. 1. Impacts of WWR variations on annual heating loads of the reference office with a conventional envelope under different façade directions in Kuujjuaq, CA, and impacts of the proposed envelope with different depths combined with a 20-cm scheduled insulated panels on annual heating loads of the reference office with 60% WWR under different façade directions in Kuujjuaq, CA.

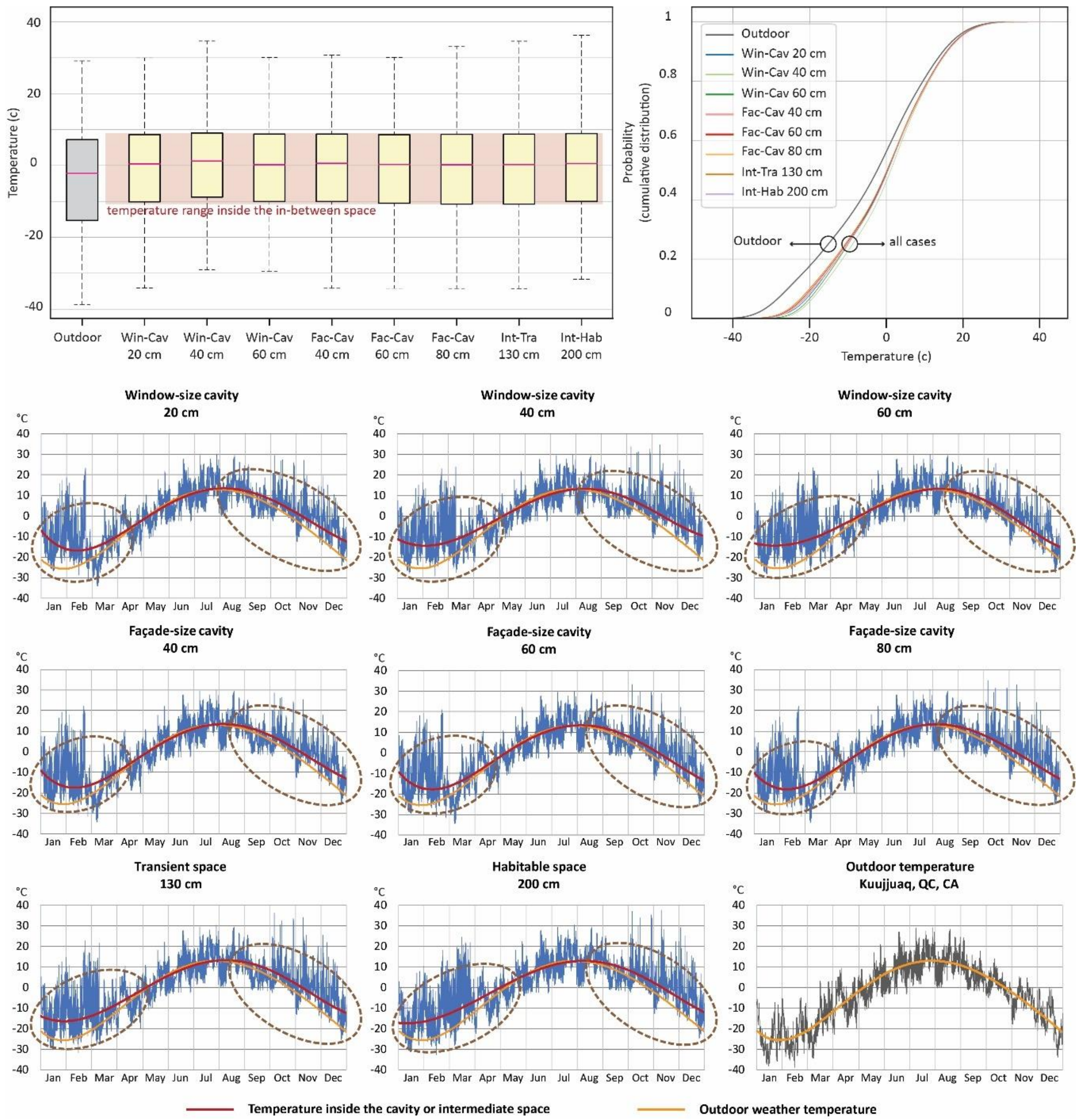


Figure 4 | A. 2. Annual air temperature behaviors inside the proposed envelope cavity/intermediate spaces with different depths compared to annual outdoor air temperature in Kuujjuaq, CA, presented as overall variations (box plot), cumulative probability distributions and hourly variations with a fitted trend line

Conclusion

This dissertation showed that biophilic and photobiological developments of adaptive high-performance envelopes for Northern Canada's buildings could enable efficient indoor-outdoor connections and foster positive occupant-nature relationships. The proposed biophilic adaptive high-performance model was shown responding to wellbeing and energy requirements related particularly to daylighting and seasonal photoperiods. The dissertation presented occupants' photobiological-psychological wellbeing challenges and shortcomings of existing building envelope practices and recommended codes for Northern Canada in relation to sub-Arctic climatic features, especially daylighting availability and strong seasonal photoperiod. Fundamental theoretical and design frameworks were developed to incorporate biophilic and photobiological indicators with adaptive high-performance envelope systems for Northern buildings. Healthy lighting performance of shading panels' variables were comprehensively characterized and adjusted to Northern climatic conditions. Results of experimental and numerical evaluations revealed higher biophilic, healthy lighting, thermal and energy performance of the proposed biophilic adaptive envelope model to address occupants' wellbeing needs and energy requirements in Northern climates compared to conventional existing envelopes. The key findings and contributions of the dissertation are concluded in terms of theoretical, architectural, and methodological aspects in relation to Northern occupants' overall wellbeing needs, as the following. Next, outlines for future studies and developments are also portrayed in relation to technical, economic, and sociocultural aspects of biophilic adaptive envelope systems and heathy buildings in Northern Canada. An outlook of dissertation is also offered at the end of the conclusions section provides a perspective of the research contributions and limitations for future studies.

Key findings and contributions

- **Photobiological approach to biophilic design**

  A fundamental theoretical framework for positive occupants' relationships with sub-Arctic nature

Integrating the idea of biophilic design with photobiological criteria in relation to Northern climatic features, particularly local daylighting availability and seasonal photoperiods, could establish a theoretical framework of positive building occupants' relationships with the harsh sub-Arctic nature. As discussed in *chapters 1 and 4*, exposure to extreme sub-Arctic phenomena could negatively impact photobiological and psychological wellbeing and limit outdoor activities and accessibility to a proper hourly/seasonal lighting dose. The dissertation explained that existing biophilic design guidelines have not characterized humans' relationships with extreme Northern climates in terms of wellbeing requirements. The photobiological approach to biophilic design established main criteria and protocols to respond to hourly/seasonal photobiological needs and prioritizing daylighting as the primary source of building lighting and biophilic qualities. Applying the proposed approach to lighting adaptation scenarios and the design of buildings and envelope systems could maximize benefits and minimize risks of extreme Northern climates for photobiological-psychological wellbeing of building occupants, i.e., identified as positive human-nature relationships.

- **Photobiological climate-based lighting adaptation scenarios**

  A strategic view to the biophilic design of envelopes and lighting systems

Rendering photobiological climate-based lighting adaptation scenarios for different building uses in relation to thermal features and Northern photoperiods offers a comprehensive overview of hourly/seasonal occupants' photobiological needs and required envelope and lighting performance. Visualizing lighting adaptation scenarios for Northern climates offering strong photoperiods could improve understanding of architects and lighting designers regarding available and required hourly/seasonal daylighting dose for proper photobiological responses in different buildings. As discussed in *chapters 1 and 2 and Annex A1*, photobiological lighting adaptation scenarios encompass parameters, thresholds, and patterns to adjust indoor lighting qualities to hourly/seasonal IF/NIF needs of occupants for different activities. Natural and artificial lighting must follow photobiological lighting adaptation scenarios. Integrating thermal and biophilic features with photobiological lighting adaptation scenarios generates patterns to optimize and control openings and shading systems of envelopes for the maximum use and adjustment of daylighting qualities to occupants' needs as well as thermal requirements in Northern buildings. Providing photobiological climate-based lighting adaptation scenarios for different buildings reveals the requirements for different lighting and envelope control strategies to optimize daylighting and thermal.

- **Biophilic adaptive high-performance envelope**

  A promising strategy for efficient indoor-outdoor connections and positive occupants-nature relationships in sub-Arctic climates

The dissertation showed that adaptive high-performance envelopes incorporated with biophilic and photobiological indicators offer a promising strategy to establish efficient indoor-outdoor connections responding to occupants' wellbeing needs and positive relationships with harsh sub-Arctic nature combined with energy-efficiency requirements. *Chapters 2 and 4* indicated that envelopes configurations and openings play key roles in responding to photobiological-psychological wellbeing and energy requirements in Northern climates through modifying visual/non-visual connections with outdoors, accessibility to daylighting availability and heat losses/gains. The shortcomings of existing Northern building envelope practices and codes as well as multi-skin envelopes to efficiently address biophilic and photobiological requirements in Northern climates were identified in *chapters 2, 4 and Annex A2*. The proposed configuration of adaptive envelopes in *chapter 4* consisted of three fundamental elements, including an optimum window size, dynamic-colored-insulated shading panels and a thermal buffer system, which could modify and optimize biophilic, healthy lighting, thermal and energy indicators. The window size of the proposed envelope model is optimized in terms of biophilic and daylighting performance indicators. The research showed that the optimum window size combined with dynamic panels could provide building occupants with efficient controllable direct visual/non-visual connections with the outdoor nature and natural phenomena. The dynamic-colored-insulated shading panels optimized healthy lighting, biophilic and thermal performance. The research indicated that the envelope configuration with dynamic-colored shading panels can potentially follow photobiological climate-based lighting adaptation scenarios and adjust daylighting qualities to hourly/seasonal IF/NIF needs of occupants in different building uses. The thermal buffer system promoted thermal, energy-efficiency and biophilic performance. The proposed biophilic adaptive high-performance envelope model was shown removing the shortcomings of plain multi-skin envelopes and existing envelope practices in Northern climates shown in Annex A2. The efficient biophilic, healthy lighting, thermal and energy performance of the proposed adaptive envelope were evaluated for a case study of an open-plan office in Northern Canada through experimental and numerical evaluations. The proposed adaptive envelope systems could be future developed for Northern buildings as discussed in the following outline section.

- **Dynamic-colored-insulated shading system**

  An integrated system to promote healthy lighting, thermal and biophilic performance of Northern buildings

The dissertation showed the effective impacts of dynamic-colored-insulated shading panels on healthy lighting, biophilic, thermal and energy indicators evaluated for a reference office under actual and simulated climatic conditions of Northern Canada. Experimental results of *chapters 3 and 4* characterized photobiological lighting performance of shading panels' variables' including (1) different cool/warm colors from strong/light bluish to strong yellowish and reddish, (2) glossy/matt reflectance, (3) horizontal/vertical orientations, (4) upwards/downwards/left/right inclinations, (5) low to high densities, (6) small to large sizes, (7) small to large openness, and (8) top/bottom positions at the window. The research evaluated impacts of shading panels' variables under different actual/simulated exterior Northern lighting conditions including actual direct sun lighting with clear skies and cool/warm diffuse daylighting of artificial overcast skies. Using prototypes of panels, including approximately 40 1:50-scale and 23 1:10-scale models, and rendering the results of lighting evaluations in false color formats and violin plots could further promote the understanding and perception of architect and lighting designers regarding the interactions among panels' characteristics and photobiological lighting parameters. Impacts of such shading panels' variables on IF and NIF responses of building occupants have not, yet, been studied. Considerable impacts of panels' color and reflectance on potential IF/NIF responses, in particular, has not been considered in designing buildings' shading devices. As shown in *chapter 4*, light bluish matt-colored panels contribute to higher NIF performance whereas yellowish matt-colored panels improve IF performance. The dissertation also characterized impacts of panels with different colored sides creating mixed impacts on lighting units related to IF and NIF depending on the horizontal or vertical orientation. Further details of panels' variables' impacts explained in chapter 4 could help architects in adapting panels' characteristics for different uses. The research adjusted shading panels' characteristics with a dynamic behavior to photobiological climate-based lighting adaptation scenarios responding to hourly-seasonal IF/NIF needs of occupants in the case study of a Northern open-plan office (Figure Con.1). Numerical analysis of *chapter 4* showed that the dynamic-colored panels could optimize biophilic performance of Northern buildings by modifying occupants' connectivity with desired/undesired outdoor sub-Arctic phenomena as well as mimicking naturalistic patterns and cycles such as day/night cycles. Numerical evaluations of *chapter 4 and Annex A2* clarified the thermal and energy-efficiency of the reference building with the thermal buffer system or multi-skin envelopes are optimized by considering the dynamic-colored panels to be made of insulation materials covering windows during nights or weekdays when daylighting is not required. Note that *Annex A2* showed multi-skin envelopes which have no dynamic-insulated panels could not optimize thermal and lighting performance of Northern buildings under different directions.

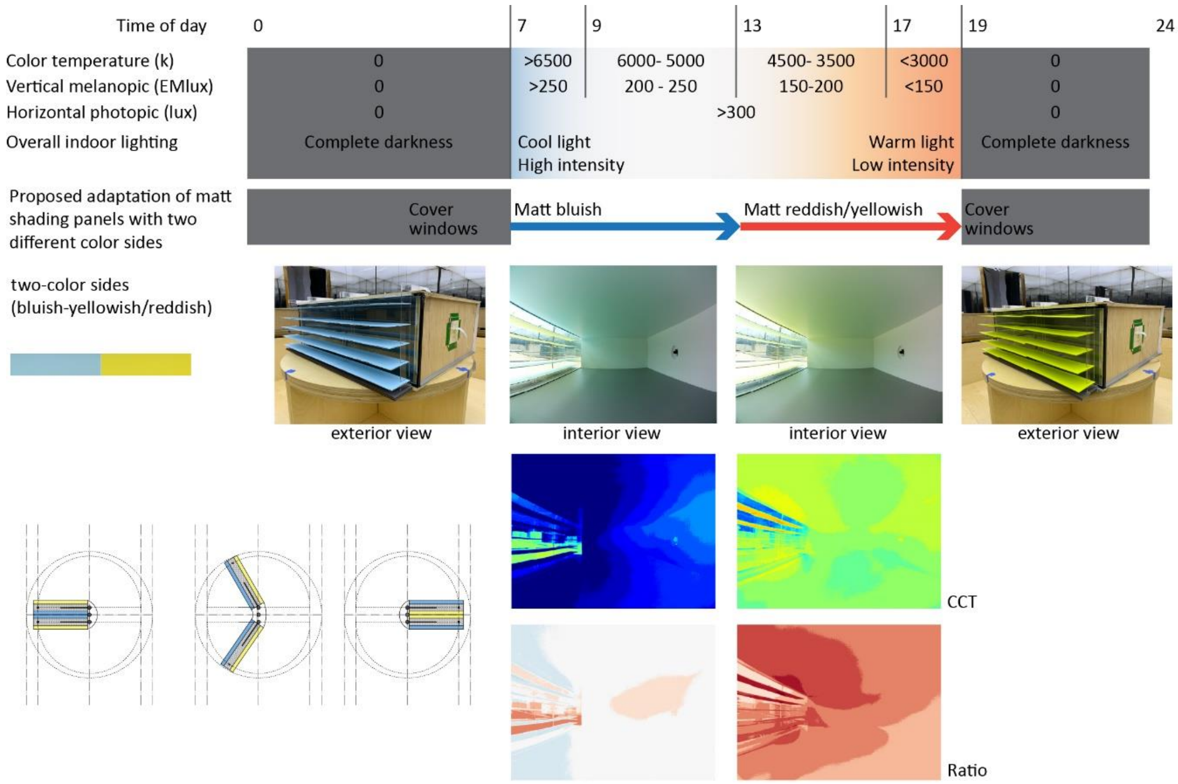


Figure Con. 1. Dynamic-colored-insulated shading system developed in the thesis

- **Integrative approach to performance and parametric design of envelopes**

  Evaluating and optimizing biophilic, healthy lighting, thermal and energy indicators

The research offered an integrative approach based on parametric and layered methodology to evaluate and optimize envelope systems in terms of biophilic, healthy lighting, thermal and energy indicators. The approach enabled characterizing interactions of envelope variables and biophilic, healthy lighting and thermal and energy parameters through integrating experimental and numerical methods. A fundamental design framework of adaptive envelope systems including main architectural variables was proposed in *chapter 2* based on the integrative performance evaluation approach for parametric studies and simplified multi-layered optimizations. As reported in chapter 4, the research employed the integrative approach with experimental and numerical methods to evaluate and optimize adaptive envelope models under Northern climatic conditions in terms of biophilic, healthy lighting, thermal and energy indicators. The first and second layers of evaluation-optimization corresponded to biophilic and photobiological indicators to address the identified challenges of wellbeing in Northern climates specified in the research objectives and context. The biophilic performance of adaptive envelopes were considered as the first evaluation-optimization layer to ensure efficient occupants' direct visual/non-visual connections with the outdoor nature through openings. The healthy lighting performance of adaptive envelopes were considered as the second evaluation-optimization layer to respond to photobiological needs and controlled connectivity with the outdoor nature. The efficient results of first and second layers were fed to the third evaluation-optimization layer corresponding to the thermal and energy performance of adaptive envelopes. The results of research showed the efficiency of the proposed integrative performance evaluation-optimization incorporated with biophilic and photobiological indicators.

- **Formulated framework and quantitative approach to biophilic envelope performance**
  Promoting systemic involvements and evaluations of biophilia in architecture

This dissertation synthesized recent biophilic guidelines and nature connectedness/relatedness studies to formulate the concept of biophilic design in relation to characteristics of human-nature relationships. As discussed in chapter 1, existing biophilic design guidelines have not, yet, offered a systemic approach or quantifiable unit to apply in architectural design processes or evaluate biophilic qualities of environment and building models/components. Biophilic guidelines describe several aspects of human-nature relationships in buildings from accessibility to daylighting to smell and sound of nature to biomimicry forms and shapes. This research integrated biophilic features related to lighting and thermal environments in healthy climate-based lighting and thermal performance indicators. The proposed formulated formwork, then, enabled discussing the state of connections among building occupants and natural systems and naturalistic features in relation to building envelopes' configurations and openings which have not been considered in lighting and thermal evaluations. The state of connections among building occupants and outdoor natural phenomena was identified in terms of (i) direct visual/non-visual connections, (ii) controllable/non-controllable visual/non-visual connections, (iii) sequential/non-sequential connections, and (iv) indirect visual/non/visual connections. The research showed that the identified state of connections was almost quantifiable offering a systemic approach to involve and evaluated during the design process or post occupancy. Analogical methods could be also used to evaluate the presented state of connections among building occupants and natural systems. The formulated framework was employed in chapter 4 to evaluate and optimize biophilic performance of adaptive building envelopes to establish efficient relationships among occupants and the harsh sub-Arctic nature. The research used numerical methods to evaluate and optimize direct visual connections of occupants with the outdoor nature in relation to opening sizes and configuration and individuals' horizontal/vertical and overall view angles towards the outdoor from different spots in the space. Controllable connections with the outdoor nature were evaluated by generating numerical models and rendering several scenes during dynamic behavior of shading panels. Image processing techniques based on per-pixel values were, then, used to compute individual exposure to outdoors and the connectivity and information richness levels during dynamic behavior of shading panels. Sequential/non-sequential connections were evaluated through using the spatial syntax graph methodology visualizing the depth and complexity of spatial organizations by numerical methods. Indirect connections with naturalistic features related to building envelopes were discussed through analogical models and reasoning related to biomimicry patterns, cycles, and colors. The presented formulated framework and quantitative approach to biophilic design could be further impacted as discussed in the following section outlining future studies.

- **Experimental lighting evaluations by using low-tech cameras and scale models**

  Improving lighting design during early design stages as well as architectural education

The experimental methodology to measure and evaluate lighting parameters by using low-tech cameras and scale models, as shown in *chapters 3 and 4 and Annexe A2*, could contribute to the architectural design process and education. The research has employed experimental set-ups to capture and visualize healthy lighting parameters in the viewpoint of potential individuals from side and back view sides inside several 1:10- and 1:50-scale models. Prototypes of buildings and spaces in different scales have commonly been used in architectural design process, especially early stages. Using scale models made of actual materials could improve the understanding and perception of architects and public about lighting design (Figure Con.2). lighting analysis by scale models could also contribute to architectural pedagogies to improve students understanding of lighting and architectural choices. Physical models, especially at large scales such as 1:10, could provide more precipitable and tangible environments to recognize lighting performance of different building components such as envelope configurations, shading devices, and surface characteristics. Commercial cameras with high dynamic range (HDR) imagery and post processing techniques could be used to visualize and evaluate healthy lighting performance in physical scale models. Rendering false color maps of different healthy lighting parameters further inform designers reading impacts of different components on healthy lighting parameters' distribution and intensities in the space. In this research, low-tech camera modules of Raspberry Pi microcomputers mounted with fisheye lenses were used to capture multiple unsaturated low dynamic range (LDR) images from very dark to very bright exposure values. LDR images were merged and calibrated to generate HDR images. Calibrated HDR images were, then, post processed based on per-pixel values to render false color maps of healthy lighting parameters including photopic and melanopic units, ratio of melanopic/photopic units, and color temperatures. False color maps expose the distribution of different parameters from the viewpoint of individuals in the space. The research, also, rendered violin plots of lighting parameters for all captured scenes providing an in-depth analysis of parameters' distributions and frequencies in the field of view. Violin plots enabled comparing impacts of different envelope's variables on healthy lighting performance of the space.

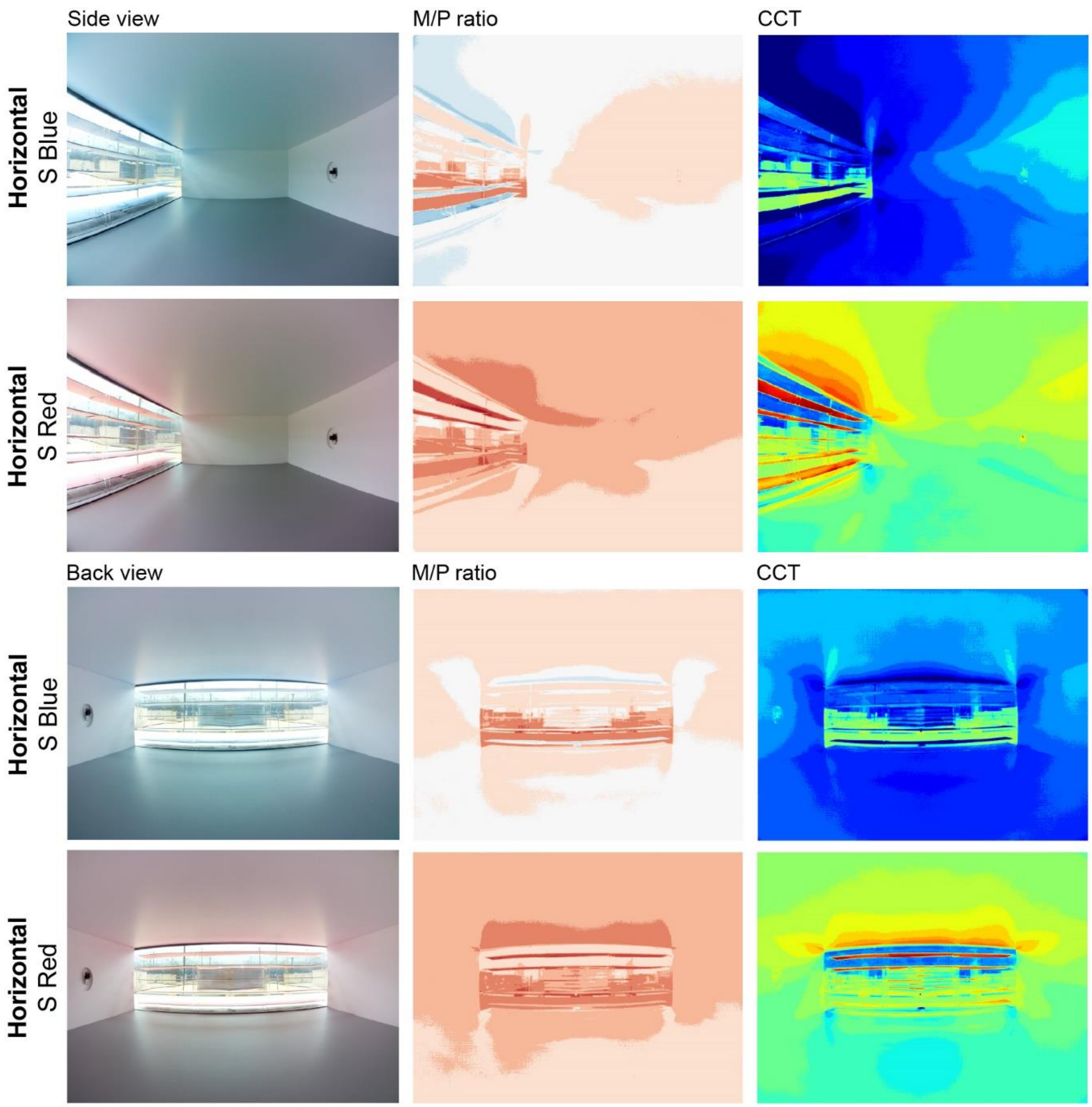


Figure Con. 2. Some examples of view and lighting analysis inside the 1:10 scale models used in the thesis

Key outlines for future studies

- **A comprehensive framework of positive human-nature relationships for Northern climates**

  Adapting restorative environmental features to climatic conditions

Efficient implementations of biophilic design in extreme Northern climates require further studies to establish a comprehensive framework of positive human-nature relationships integrated with restorative environmental features. The concept of connections with natural phenomena offered in biophilic design should be characterized in relation to extreme climatic features and humans' wellbeing thresholds. Humans' physical, photobiological and psychological wellbeing thresholds limit the relationship with harsh nature. Uncontrollable/unprotected humans' interactions with sub-Arctic climates could negatively impact physical, photobiological and psychological wellbeing. For example, the very cold weather of Northern climates during the winter could have several risks for physical health and prevent an adequate daily promenade, especially with insufficient warm clothing. Strong photoperiods could have negative photobiological impacts by desynchronizing internal body clocks and causing sleep disorders. Exposure to several days of dark overcast skies, long dark days, and low interactions outside buildings could stimulate negative psychological responses such as a down mood or depression. As discussed in the dissertation, existing biophilic design guidelines have not, yet, established a framework for positive human-nature relationships in extreme climates. This research has focused on photobiological wellbeing and developed a framework to incorporate photobiological factors with biophilic design for Northern climates. However, biophilic design must be integrated with a comprehensive strategic framework of positive human-nature relationships encompassing thresholds of humans' physical, photobiological and psychological wellbeing responses to extreme climatic conditions. Formulating restorative environmental features applicable to extreme climatic conditions in relation to the framework of positive human-nature relationships could characterize efficient biophilic design approach in sub-Arctic climates.

- **A systemic methodology with quantifiable units and spatiotemporal scales for biophilia**

  Promoting biophilic evaluations in architectural design and post occupancy

Existing biophilic design guidelines and recommendations lack a systemic methodology and quantifiable units to apply and evaluate biophilic qualities during different stages of architectural design processes to post-occupancy. Main references of biophilic design are descriptive which are intuitive to use. References have not, also, proposed any quantitative/qualitative method or quantifiable unit with a scale system to measure, calculate and evaluate the intensity, magnitude, and distribution of different biophilic features required/existing in various spaces and buildings with different sizes. References have not also determined the temporal scale of exposure to different biophilic features in relation to humans hourly/seasonal wellbeing requirements. Thus, the main questions of how and to what extent (spatial and temporal) it should/could apply biophilia in a building or a design process remain unanswered. This research showed that biophilic design could be formulated and numerically evaluated in terms of characteristics of connections among occupants and nature related to envelope configurations. The proposed methodology could be further developed to establish a systemic methodology to apply, measure and evaluate biophilic qualities for different buildings. To this end, several items, and attributions of biophilic design recommendations overlap with lighting, thermal and indoor air quality standards. Biophilic qualities could be integrated with the available metrics and standards for such items. For example, biophilic guidelines highlight occupants' connections with daylighting and the sun. Meanwhile, several standards and metrics have been developed to evaluate daylighting performance of buildings. It could integrate the biophilic highlight with the existing standards and metrics to prioritize and maximize efficient daylighting in buildings. As another example, biophilic design emphasizes accessibility to natural air and temperature and gradual temperature variations around occupants' bodies. This highlight could be quantified by integrating with indoor air quality and thermal standards and metrics through which building occupants could be provided with sufficient natural air and acceptable variations in the ambient air temperature. Developing integrated biophilic standards and metrics of such items could enable adjusting the intensity, magnitude, and distribution of biophilic qualities to thresholds of humans' wellbeing responses in each category. Yet, some items and attributes of biophilic design recommendations are not particularly overlapped with other standards and metrics, for example, direct/indirect visual connections with greenery and vegetation inside the space and or through views of the outdoor landscape or by looking at an image. Many nature connectedness/relatedness studies have been conducted evaluating wellbeing impacts of greenery and vegetation in different sizes and configurations, for example an actual or an image of plants in the office or view of outdoor trees. Such studies could be synthesized to develop a metric/unit correlating the size, configuration, and spatiotemporal distribution of greenery and magnitude of positive/neutral/negative wellbeing responses applicable to architectural and environmental evaluations. Therefore, conducting further multidisciplinary studies could enable developing a systemic methodology with quantifiable units and appropriate spatiotemporal scales for biophilic features to be effectively used in architectural design processes and post occupancy evaluations.

- **Integrative healthy lighting performance of envelopes and interior spaces' characteristics**

  Interactions of interior/exterior shadings with surfaces of indoor/intermediate spaces

Further studies should be conducted to evaluate healthy lighting performance of different interior and exterior shading devices such as curtains, blinds, shutters, louvers, overhangs, and projections, in terms of different surface characteristic variables especially color and reflectance. Experimental results of chapters 3 and 4 showed considerable impacts of shading panels characteristics, in terms of different surface variables, on healthy lighting parameters under actual/artificial Northern daylighting conditions. Experimental healthy lighting studies with scale physical models of different shading devices, similar to methods and scenarios conducted in this dissertation, could be performed to portray impacts of different surfaces and develop proper adaptation strategies for different building uses. Furthermore, healthy lighting performance of shading systems could be also studied in relation to surface characterises of indoor and intermediate spaces. Changing the surface color and reflectance of indoor and intermediate spaces can potentially modify daylighting spectrums and respective health-related parameters. Interactions of shading and interior surfaces' characteristics could produce different impacts on healthy lighting parameters. Healthy lighting impacts of surface characters could be also changed under different interiors' artificial lighting conditions used most often during days in deep spaces with low daylighting penetration ratio. Therefore, future studies must characterize healthy lighting performance of shading devices and indoor/intermediate spaces' surface characterises under different exterior and interior daylighting conditions in order to enable architects and designers to adjust configurations of different spaces for efficient photobiological responses of occupants.

- **Overall occupants' wellbeing considerations in Canada building and energy codes**

  Prioritizing biophilic adaptive high-performance envelopes

As discussed in the dissertation, existing Canada building and energy codes for Northern climates are mainly focused on reducing energy consumptions of Northern buildings and satisfying biological thermal/lighting comforts by using mechanical and artificial systems. However, results of the dissertation indicated the deficiencies of existing Canada building and energy codes to fulfil photobiological-psychological wellbeing of occupants in Northern climates. The scoping literature review also revealed that several other studies and researchers have also shown the shortcomings of existing building codes to address different aspects of Northern occupants' wellbeing. As a promising solution, experimental and numerical results of this dissertation showed that biophilic adaptive high-performance envelopes offer a promising solution to respond to photobiological-psychological wellbeing needs of Northern occupants through (energy-) efficient connections with outdoors.

Therefore, this dissertation calls for the transformation of Canada building and energy codes for Northern climates to consider overall wellbeing requirements and prioritize/recommend appropriate adaptation strategies as the proposed adaptive envelope model. To this end, further research must be conducted to explore and optimize different adaptive architectural strategies and mechanisms for Northern climates. Adaptive strategies and systems should be evaluated through integrative performance evaluations considering overall wellbeing and energy-efficiency requirements in terms of biophilic, healthy lighting, thermal and energy indicators.

- **Lifecycle, durability, and economic assessments of biophilic adaptive envelopes:**

Efficient applications of the proposed biophilic adaptive high-performance envelope in Northern climates require further studies in terms of durability, resilience, and robustness of materials and mechanical systems as well as economic aspects. This research has not evaluated durability, resilience and robustness of different materials and mechanical operative systems for the proposed adaptive envelope system under extreme Northern climatic conditions. The research has not, also, evaluated the economic efficiency of the proposed adaptive envelope system. The research has focused on the efficiency of the proposed envelope to reduce energy consumptions for heating in the case study of a Northern office. Future studies must evaluate durability, resilience and robustness of different materials and mechanical systems applicable to the proposed systems under Northern conditions in order to develop highly durable and resilient and robust adaptive envelope systems. Special attention must be given to the material of the exterior skin in terms of potential condensation and freezing. This research has mainly evaluated the potential efficiency of a single glazing skin for reducing energy consumption of the reference building. However, future research should address the risk of condensation as part of the system's durability and resilience in relation to the airtightness of the exterior/interior skin, different glazing types, such as double or triple, and scheduled auxiliary mechanical ventilation. Deep learning analyses and data mining approaches could be conducted to detect faults and failures of different systems, materials, and configurations. Future studies require to evaluate overall economic efficiency of a durable resilient adaptive envelope system during an efficient life cycle.

- **Transient/habitable intermediate spaces integrated with potentials for cultivations**

  A higher biophilic energy-efficient strategy for Northern buildings

Exiting Northern building practices and codes have not given special attention to potentials of different configurations of transient and habitable intermediate spaces to improve biophilic and thermal performances and occupants-nature relationships under sub-Arctic climatic conditions.

General information is given for applying vestibules around Canada. No particular recommendation is issued to adapt and apply different typologies and configurations of intermediate spaces to Northern climates and buildings. Results of this dissertation showed that adaptive envelope models with transient/habitable intermediate spaces could promote biophilic, thermal and energy efficiency of the reference building in Northern Canada. Transient and intermediate space could be further developed to act as a greenhouse offering potentials for farming and cultivating plants and vegetations. As food security and supply becomes a growing concern in Northern climates, attentions are directed towards greenhouses and indoor farming under extreme climatic conditions. Integrating potentials for cultivating vegetation and farm products within intermediate spaces could benefit Northern communities' food security in addition to buildings' thermal and biophilic efficiencies. Developing such cultivating transient/habitable intermediate spaces could also improve overall biophilic qualities of Northern buildings where people could interact directly with nature and spent more time inside a transparent protected space exposed to outdoor natural phenomena. Applications of such intermediate spaces, yet, require special attention to risks of condensation and freezing and potential high cost of plants' maintenance under extreme Northern climatic conditions. Economic aspects and life cycle assessments of cultivating transient/habitable intermediate spaces must be studied in future research. Further studies must be also conducted in terms of using appropriate plants and vegetation with proper methods for watering, lighting, and cultivations under sub-Arctic conditions in relation to the durability of building components and indoor air quality.

- **Sociocultural studies of biophilic photobiological adaptive envelopes in Northern climates**

  Promoting cultural integrations and social acceptability in Inuit communities

Biophilic design and adaptive building envelopes should incorporate the sociocultural contexts of Northern people. Indigenous Northern people of Canada, in particular Inuit, have developed a rich culture and an adapted vernacular architecture based on positive relationships to Arctic and sub-Arctic Nature during several centuries. The history of Inuit identifies the unique culture, architecture, art, language, diet, transportation, and clothing inspired from and adapted to the Arctic nature. Inuit unique cultural features inspired from the Arctic nature were reflected in their architecture, for example, the use of local materials to build igloos, Thule dwellings, whalebone house, inuksuk adapted to strong seasonal variations. The social context of Inuit communities is different from the southern mixed-culture cities of Canada. Social values and rules in Inuit communities and families are adapted to challenging living conditions in extreme Arctic climates. However, modern architecture and recent settlements and building models developed for Inuit in Northern Canada have not been adapted to sociocultural contexts in addition to the climatic context. Recent settlements and building models have most often been built based on experiences and practices in southern mixed-culture Canadian cities. Several social and cultural challenges related to settlement and buildings have been raised in Inuit communities. Sociocultural acceptability is an important indicator for successful implementations of biophilic design and adaptive architecture. More critically, the notion of nature and natural systems, including color and lighting variations, as well as buildings' energy efficiency could be different in Inuit cultural and social contexts. Therefore, this research calls for further multidisciplinary architecture-based studies integrating Inuit cultural motifs and social values in biophilic and lighting design and adaptive architectural practices such as the proposed envelope model. Mixed methods multidisciplinary studies linking architectural, anthropological, and behavioral studies could enable establishing an architectural-sociocultural framework to detect and reflect cultural features in buildings. Such mixed methods multidisciplinary research could be conducted to develop an adapted sociocultural framework of biophilic design for Northern indigenous communities. Methodologies and approaches must be developed to translate outcomes of anthropological and social studies about Inuit into an architectural vocabulary applicable to architectural design processes. Inuit cultural interpretations of Arctic nature, light, midnight sun, polar nights, landscape and color variations, and seasonal changes must be explored and translated into the architectural language and practical architectural modeling and strategies. Forms of Northern buildings and shading panels could be adapted to cultural motifs and interpretations of Northern indigenous people. Qualitative approaches and interpretative methods, such as semiotic, could be employed to perform the intertextual translations from anthropological and social sciences to architecture. Architects, anthropologists and sociologists and influential decision-makers could employ co-design, workshops, and participatory strategies to effectively interact with indigenous people and apply their sociocultural aspirations into the architectural and environmental design processes, including biophilic design of building envelopes and lighting environments. Conducting such participatory architecture-based research and development projects with indigenous communities could promote Inuit access, ownership, and control over data and information as well as build capacity in Inuit research which are aimed in the Canada's National Inuit Strategy on research.

Outlook

This dissertation provides a perspective to positive occupants' relationships with sub-Arctic nature by integrating biophilic design with photobiological factors to develop adaptive high-performance envelopes which could enable efficient indoor-outdoor connections responding to wellbeing and energy requirements. The research developed a photobiological approach to biophilic design and envelope configurations in relation to climatic conditions which was used to visualize lighting/thermal adaptation scenarios. An integrative architectural framework of biophilic adaptive envelopes was proposed based on the biophilic-photobiological theoretical framework which enabled adjusting biophilic, healthy lighting, thermal/energy indicators in relation to climatic context and occupants needs, particularly in Northern latitudes. The biophilic-photobiological theoretical framework and integrative architectural framework of biophilic adaptive envelopes fulfil occupants' wellbeing needs in relation to sub-Arctic climates and building envelopes. Healthy lighting performance of shading panels' characteristics were compressively evaluated which could enable adjusting lighting in relation to hourly/seasonal photobiological needs of occupants. The research employed the theoretical and architectural frameworks and shading panels' lighting performance to develop adaptive high-performance envelopes incorporated with biophilic and photobiological factors for Northern buildings. Integrating experimental healthy lighting evaluations with numerical biophilic, thermal and energy assessments enabled further understanding lighting, biophilia, and thermal issues during early stages of architectural design processes. Results of biophilic, healthy lighting and thermal/energy performance evaluations suggest considering the biophilic adaptive high-performance envelope model as a promising architectural strategy to improve public wellbeing and energy efficiency in Northern communities and reduce negative impacts of Northern buildings on nature and occupants. The research calls for special attention to potentials of biophilic adaptive envelope systems and the integrated photobiological-biophilic approach in Canada building and energy codes for Northern climates.

Efficient implementations of the proposed adaptive high-performance envelope model and integrated photobiological-biophilic approach in Northern Canada, yet, require addressing limitations of this dissertation especially in terms of technical, economic, and sociocultural issues as discussed in the key outlines. As this research focused on photobiological and biophilic aspects of connectivity with sub-Arctic climates through envelopes, the technical issues of adaptive envelopes' implementations in Northern climates have not been studied. Future research should study the technical issues of adaptive envelopes in terms of durability, resilience, and robustness of material and mechanical components, especially for potential risks of condensation and freezing on the exterior skin.

Economic aspects of the biophilic adaptive envelopes and photobiological-biophilic approach during an efficient life cycle in Northern climates have not been assessed because the research was aimed at improving photobiological-psychological wellbeing factors through energy-efficient biophilic adaptive envelopes. The research, yet, showed energy saving potentials resulted by applying the biophilic adaptive envelope to an open-plan office in Northern Canada compared to the conventional façade. Future studies about the economic efficiency of adaptive envelope systems and biophilic design in addition to energy saving potentials should be conducted to further attract stakeholders' and policymakers' attention. Socio-cultural aspects of envelopes and biophilic design were not considered because the dissertation was directed towards bio-psychological wellbeing and energy factors in relation to physical environmental factors, building physics and envelope structure. Integrating socio-cultural motifs and vernacular architectural features of Inuit with the proposed envelope systems and theoretical-architectural approaches should be studied in future research through collaboration with local communities and participation of indigenous people. Developing multidisciplinary architecture-based studies through participatory approaches with Northern indigenous communities could ensure Inuit access, ownership, and control over data and information as well as build capacity in Inuit research, as prioritized in the National Inuit Strategy on research.

The overall outcomes of this dissertation, specifically the photobiological-biophilic approach, healthy performance of shading panels' characteristics, and biophilic adaptive envelope systems, could enlighten architect, designers, and policymakers about potentials of architectural adaptation strategies for envelopes to enable efficient indoors' connections with extreme Northern climates based on constituting the concept of positive occupants' relationships with the outdoor harsh nature. The outcomes of this research could be used to promote building performance and occupants' wellbeing in similar climatic conditions around the world.

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Annexe A1. Photobiological climate-based lighting adaptation scenarios for high-performance biophilic buildings

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A1.1 Abstract

The aim of this research is to develop climate-based lighting adaptation scenarios for proper photobiological responses in high-performance biophilic buildings throughout the year. Photobiological responses refer to image forming (IF) and non-image forming (NIF) effects of light after reaching human eyes. IF effects enable vision. NIF effects regulate circadian clocks, alertness, and mood. A proper intensity and colour temperature of lighting must be provided at the proper time of the day in response to hourly IF and NIF requirements of building occupants for different activities. This research has conducted a scoping literature review to synthesise main factors and criteria for adjusting lighting to IF and NIF needs in different buildings. The research, then, developed different patterns for lighting adaptations in office, educational, residential and health care buildings based on the synthesised factors and criteria. The proposed lighting scenarios are adapted to the local photoperiod of Cambridge Bay, in Northern Canada, as a case study. The results are discussed to outline major issues for future developments including an annual monitoring and analysis of daylighting intensity and colour temperature in sub-Arctic climates to determine the potential daylighting dose available to people at different times of the day.

A1.2 Introduction

This study aims at developing lighting adaptation scenarios adapted to local photoperiods to address occupants photobiological needs in high-performance biophilic buildings. Lighting adaptation scenarios are identified as protocols and profiles to adjust lighting parameters of the environment to photobiological needs of occupants during the day [263, 316]. Photobiological studies and the human-centric lighting approach have, recently, drawn attention to impacts of lighting and photoperiods, i.e. day/night cycles, on building occupants' wellbeing [262]. Photobiological impacts of light are identified as image forming (IF) and non-image forming (NIF) effects [65, 241, 262]. Image forming (IF) effects correspond to biological responses of human eyes to the incident light at the corneal enabling vision and formation of images in the brain. Non-image forming (NIF) effects refer to biological processes of light received by ipRGCs photoreceptors of eyes which regulate circadian clocks, alertness, sleep-wake cycles, performance and mood [13, 50, 294]. IF and NIF responses of occupants depend on the time and duration of exposure, intensity, and spectrum of the incident light for different activities [13, 50, 58, 294]. NIF responses are particularly synchronized and reset by the local photoperiod [43, 123, 242]. Providing sufficient darkness for sleeping areas or bedrooms adapted to the human body's biological night is also required to regulate sleep-wake cycles [13, 42, 185].

Developing photobiological climate-based lighting adaptation scenarios provide fundamental protocols to promote biophilic qualities and overall performance of buildings [262, 263, 283, 316]. High-performance biophilic buildings must enable efficient and positive accessibility to daylighting and local photoperiods in response to occupants' IF and NIF requirements for a particular activity as well as energy efficiency issues [263, 283]. The main characteristic of biophilic buildings is immersive connectivity with outdoor natural phenomena including daylighting and photoperiods [1, 3]. High-performance buildings are focused on maximizing the positive use of daylighting and solar radiation to reduce artificial lighting uses and energy consumption of lighting and thermal systems [149]. Developing lighting adaptation scenarios could effectively contribute to occupants' wellbeing and buildings' thermal and lighting performance especially in high-latitude Northern regions towards the Arctic which offer extreme seasonal variations in photoperiods and weather temperatures.

This research synthesised several recent studies and recommendations regarding photobiological and human-centric lighting to produce climate-based lighting adaptation scenarios for typical office, educational, residential and health care buildings in Cambridge Bay, Nunavut, Canada (Lat. 69° N, Long. 105° W), as a case study. The synthesized literature enabled establishing criteria and patterns to adapt lighting parameters to occupants' photobiological needs in the specified building uses in response to the local daylighting availability. The generated lighting adaptation scenarios are presented and discussed to outline main issues for future developments.

A1.3 Methodology

A scoping literature review was conducted to synthesise major recommendations and studies which are recently published regarding human-centric and photobiological lighting impacts. The studies were categorized and evaluated in terms of main factors affecting occupants' IF and NIF responses in relation to the lighting design of buildings, biophilia and local photoperiods. Recommended parameters, units, patterns, and threshold for proper IF and NIF impacts of lighting in office, educational, residential and health care buildings are synthesized. Lighting scenarios encompassing the essential units and thresholds are, then, adapted to the local photoperiod and daylighting availability published by the typical meteorological year [315] and Marsh [311].

A1.4 Results and discussion

A1.4.1 Recommended factors and criteria

The recommendations and studies on photobiological lighting were mainly focused on intensity of different light spectrums in relation to timing and duration of impulses received at individuals' eyes [12, 13, 32, 50, 57, 58, 65, 68, 80, 83, 89, 91-94, 185, 216, 241, 262, 294, 303, 317-320]. Table 1 summarizes the parameters and respective metrics, units, and target plans for measurements that have most often been used to evaluate intensity and spectrum of lighting in relation to potential IF and NIF effects. As displayed in Table 1, the light intensity affecting IF responses are discussed in terms of illuminance in lux, or photopic lux, corresponding to the photopic spectral luminous efficiency function of human eyes. NIF impacts of lighting intensities are mostly discussed in terms of the melanopic equivalent daylighting (65) illuminance in MED-lux or EM-lux, circadian stimulus in CS and corneal illuminance in lux [12, 94, 294, 319]. Such metrics have been used in different studies. There is, yet, no consensus on a single specific metric to discuss NIF effects. The melanopic equivalent daylighting (65) illuminance corresponds to the melanopic (ipRGC photoreceptors of human eyes) action spectra. The (equivalent) melanopic unit presents the equivalent melanopic quantity produced by the standard daylighting (D65) [294, 321]. The melanopic daylight (D65) efficacy ratio is identified as the ratio of melanopic efficacy of luminous radiation for a source to the melanopic efficacy of luminous radiation for daylighting (D65) presented in mW/lm [294, 321]. The melanopic efficacy ratio is also reported in terms of the ratio of melanopic efficacy of luminous radiation to the photopic (luminance) efficiency of the luminous radiation in mW/lm [127, 244, 294, 321]. The ratio could be used to calculate melanopic units from photopic units. The circadian stimulus corresponds to the spectral sensitivity of the human circadian system based on the acute melatonin suppression [94, 319]. The corneal illuminance unit refers to vertical illuminance received at the eye surface. The lighting colour is also discussed for potential impacts on visual performance (IF effects) and circadian systems and alertness (NIF effects). Lighting colour impacts on visual performance are mainly discussed for artificial lighting sources in terms of colour rendering indicators. The colour rendering index (CRI) is most often used to represent the ability of a light source to reveal the colour of objects identical to an ideal or natural light source [13, 50, 58]. Lighting colour temperatures correspond to the temperature of a blackbody radiator emitting identical colour as the light source reported as correlated colour temperature (CCT) in kelvin (K) [13, 50, 58]. Lighting colour temperatures are mostly discussed in the context of NIF effects as cool lighting could generally produce higher impacts on circadian systems and melatonin sections/suppressions compared to warm lighting. Most studies emphasized that colour temperature and intensity units for NIF effects of a light source or a space must be considered together where NIF impacts of a cool lighting with a low intensity could be similar to a warmer lighting with a higher intensity. For example, 300 lux of a 6000 K light source could produce CS of 0.3 similar to 400 lux of 4500 K light source [319].

Table A1. 1. Lighting parameters related to IF and NIF effects

Factor	**metric**	**unit**	**Target surface**
Intensity of light for IF effects	Illuminance	lux	Horizontal plan at the height of the work plan
Intensity of light for NIF effects	Melanopic equivalent illuminance	MED-lux or EM-lux	Vertical plant at the height of the individual's eye
	Melanopic daylight (D65) efficacy ratio	mW/lm	
	Circadian stimulus	CS	
	Corneal illuminance	lux	
Colour of light for IF effects	Colour rendering index (CRI)	CRI	Not specified
Colour of light for NIF effects	Correlated colour temperature (CCT)	K	Not specified

The timing and duration of exposure to different lighting have widely been studied for potential NIF effects. NIF impacts of lighting have studied for four periods of the day in relation to humans' circadian clocks that include (1) 7h to 9h, (2) 9h to 13h, (3) 13h to 17h, (4) 17h to 19h, and (5) biological night from 19h to 7h. Studies have, generally, recommended cool high intensity lighting in the morning until 13h followed by warm lighting in the afternoon and warm low-intensity lighting in the evening. Occupants must not experience darkness during the day [319]. A complete darkness must be provided during the night. Thresholds for lighting intensities during each period depend on the individuals' activity in the space. In general, one to two hours of cool bluish lighting, above 6000 K, with an intensity of at least 0.3 CS or 200-250 EM-Lux are recommended for the early morning from 7h to 9h. Whitish lighting with around 5000 to 6000 K and around 0.3 CS or 200-250 EM-lux is proposed for until 13h. warm lighting of around 3500-4500 K with an intensity of 0.2 CS or 150-200 EM-lux is suggested for the afternoon from 13h to 17h. Warm lighting of lower than 3500 K and 0.15 CS or 150 EM-lux is offered for the evening around 17h to 19h or two hours before sleeping.

A1.4.2 Photobiological climate-based lighting adaptation scenarios

This research synthesized the recommended parameters and thresholds to propose lighting adaptation scenarios responding to IF and NIF needs of occupants in different buildings in Cambridge Bay. Extreme seasonal variations in the photoperiod of Cambridge Bay could negatively affect internal body clocks of both indigenous and non-indigenous people. Figure A1. 1 shows the Cambridge Bay's seasonal period and hourly photopic and equivalent melanopic lux offered to people during the year. The photopic illuminance was considered as the sum of direct and diffuse illuminances offered in the typical meteorological year. Equivalent melanopic lux was calculated by assuming direct solar illuminances as D65 daylighting and diffuse illuminances as D75 overcast skies. The equivalent melanopic efficacy ratios of such daylighting spectrums were extracted from CIE-S-026 alpha-opic Toolbox [300]. The total melanopic illuminances were derived from the sum of direct illuminances multiplied by the D65 efficacy ratio and diffuse illuminances multiplied by the D75 efficacy ratio. In the Arctic and sub-Arctic regions, misalignment of circadian clocks, sleep disorder and day/night confusions have most often been reported in the summer and winter which are potentially related to daylighting conditions, polar days and polar nights [41, 42, 132, 182, 183, 185, 322]. Therefore, lighting adaptation scenarios require addressing human needs for darkness during polar days especially in sleeping areas such as bedrooms. Figure A1. 1 shows the synthesised daily lighting adaptation scenarios for office, educational, residential and health care buildings during typical summer and winter days in Cambridge Bay. Figure A1. 2 presents the daily patterns for lighting intensities and colour temperatures for proper IF and NIF responses at the proper time of the day. Figure A1. 3 shows the synthesized seasonal lighting adaptation scenarios developed for the specified buildings in Cambridge Bay.

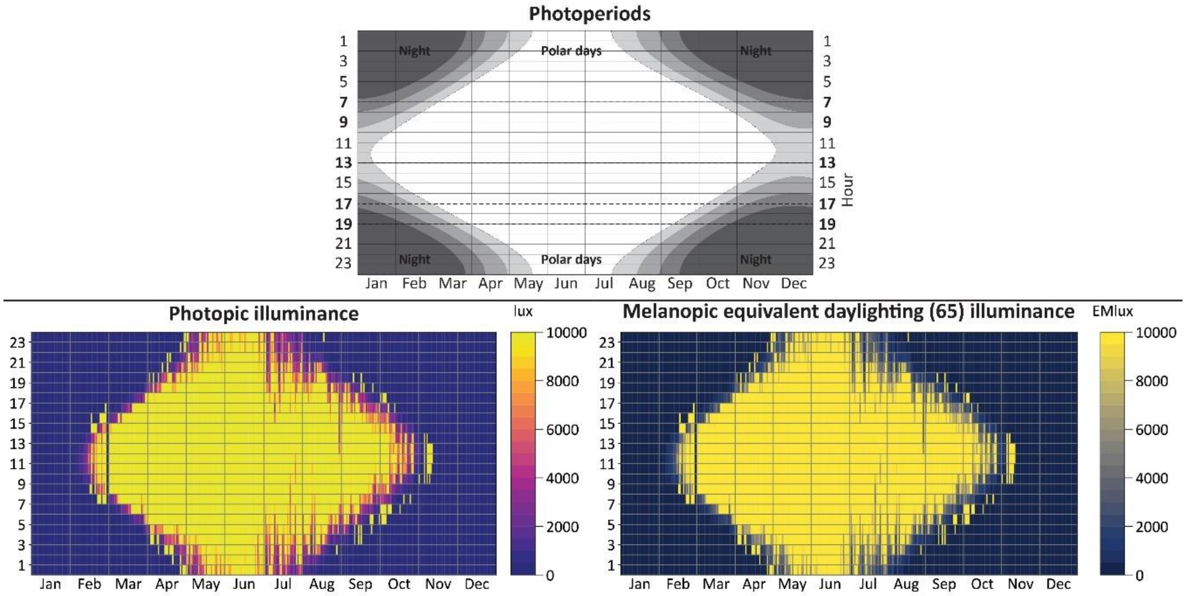

Figure A1. 1. Cambridge Bay’s photoperiod and daylighting dose

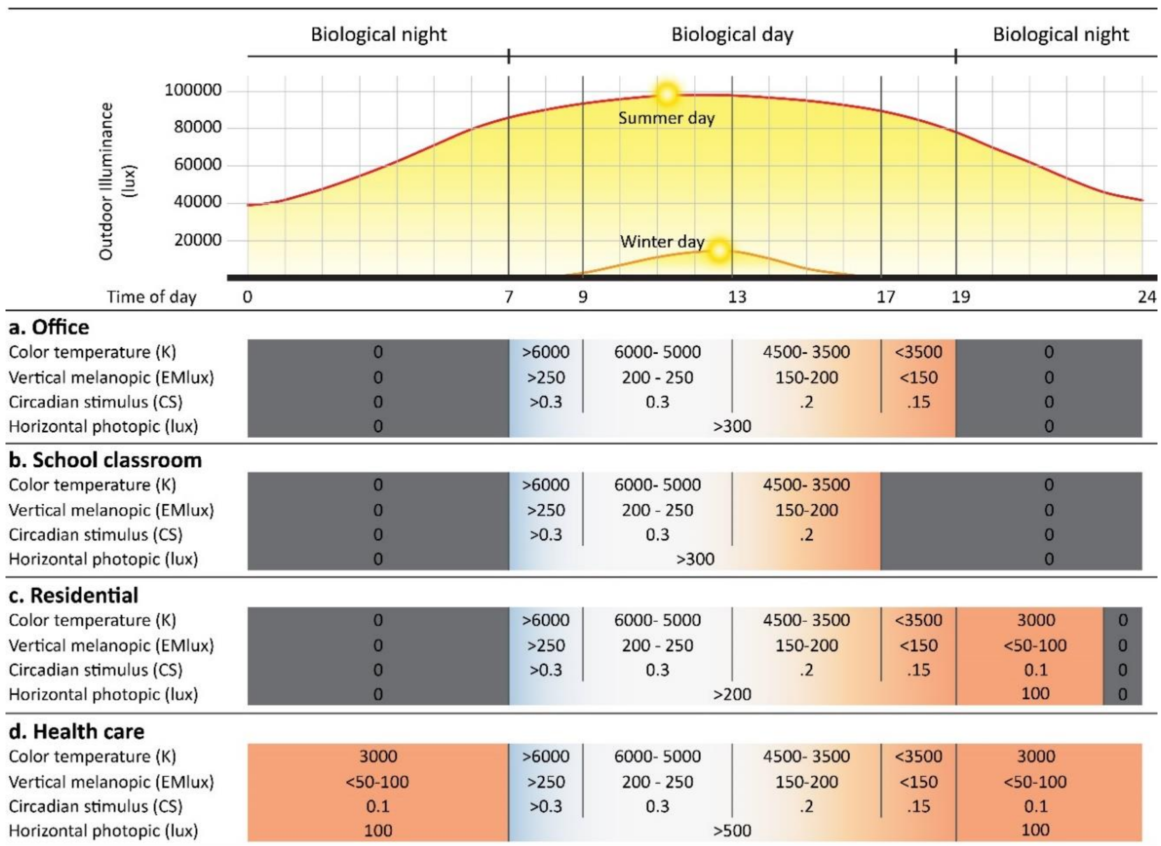

Figure A1. 2. Daily photobiological lighting adaptation scenarios developed for different buildings during typical summer and winter days in Cambridge Bay, Nunavut, Canada

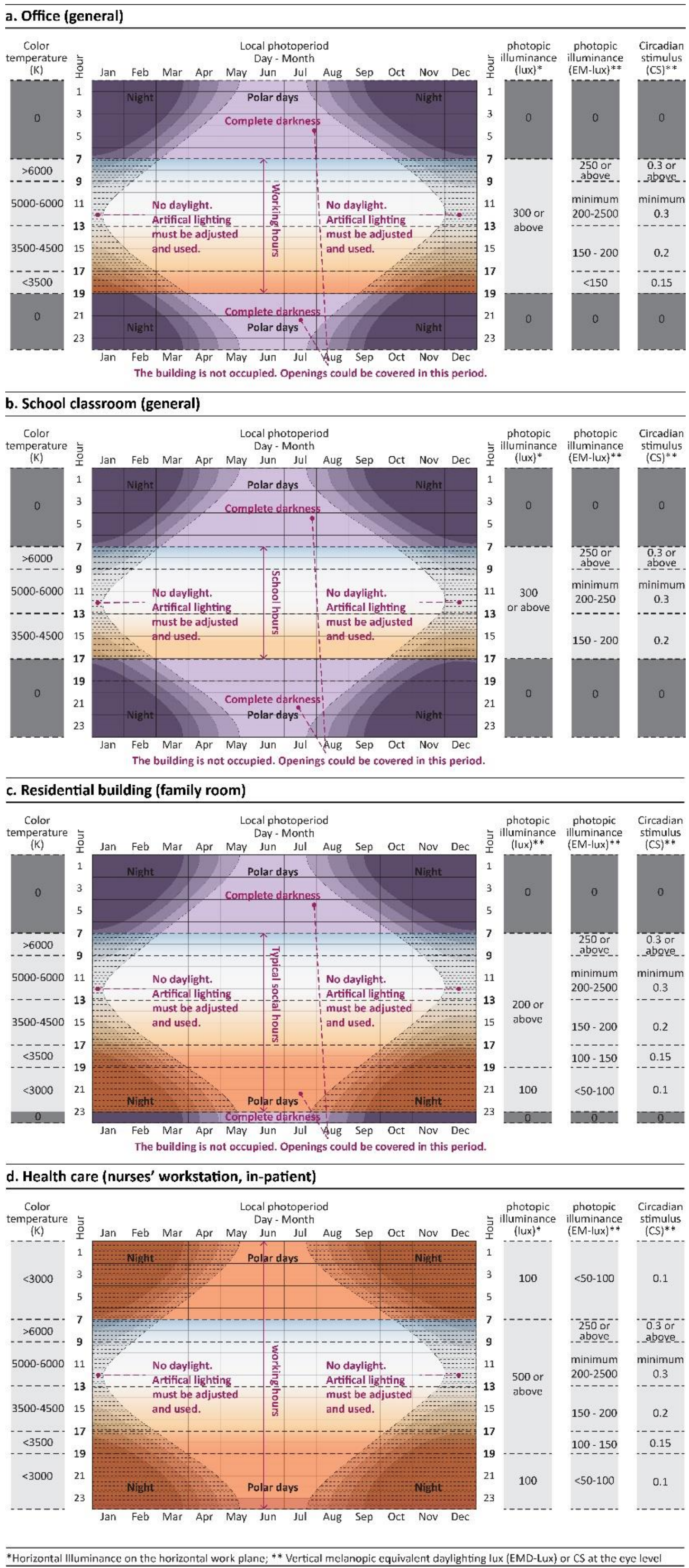

Figure A1. 3. Seasonal photobiological lighting adaptation scenarios developed for different building in Cambridge Bay, Nunavut, Canada

The local photoperiod depicts day and night times corresponding to sunrise, sunsets, twilight, and night hours throughout the year. The period of working, school, or social hours are highlighted for each case study. The working hours for the office are considered from 7h to 19h. The school hours are assigned for 7h to 17h. The social hours for the residential building are assumed from 7h to 23h. Nurses' working hours are considered for the entire day. The hatched periods show the potential hours requiring artificial lighting. Right columns represent the proper intensity of lighting at the proper time of the day to respond to IF and NIF needs in each space. The intensities are presented in terms of illuminance at the horizontal work plan and melanopic equivalent daylighting (D65) and circadian stimulus at vertical plan at the eye level as synthesized from the reviewed studies. The left column presents the potential colour temperatures of lighting at the proper time of the day in response to IF and NIF requirements in the space. Artificial lighting using LED systems must be used during polar nights and short days of winters to respond to photobiological needs of occupants. The proposed lighting adaptation scenarios, also, highlight the periods that complete darkness must be provided in the space. During such periods, the openings could be fully covered, for example, by insulated panels to prevent potential heat losses under the extreme cold arctic climatic conditions. Thus, building lighting systems could be designed and operated based on the provided patterns to respond to photobiological needs of occupants while improving the overall performance.

A1.5 Conclusion

Photobiological climate-based lighting adaptation scenarios are essential for high-performance biophilic buildings, especially in sub-Arctic climates. This paper provided the main factors and criteria to develop lighting adaptation scenarios for proper IF and NIF responses in different buildings. The proposed lighting scenarios are adapted to local photoperiods. The developed scenarios offer patterns to adapt timing and duration of intensities and colour temperature of lighting, including natural and artificial, for some examples of building uses in Northern Canada. Future research must study the intensity and colour temperature of local daylighting under different sky conditions in terms of parameters representing NIF effects in order to identify potential doses of lighting exposed to people at different times of the day. Lighting adaptation scenarios could be further integrated with the thermal and lighting smart control systems to increase the overall performance of buildings. Adaptive mechanical shading panels could use lighting adaptation scenarios to adjust indoor daylighting performance of buildings for proper IF and NIF requirements.

A1.6 Acknowledgements

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Annexe A2. Single-skin and multi-skin building envelopes in extreme sub-Arctic climates: biophilic, healthy lighting and thermal performance evaluations

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A2.1 Abstract

This research aims at studying the potentials of single-skin and multi-skin envelopes with different window sizes to promote biophilic, healthy lighting and thermal performance of buildings in extreme sub-Arctic climatic conditions. Single-skin envelopes with low window-to-wall ratios (WWR) are most often recommended for sub-Arctic climates to reduce heating loads. Potentials of multi-skin envelopes to address biophilia and healthy lighting combined with energy-efficiency factors in such climates have not, yet, received sufficient attention. Five envelope models are evaluated including two single-skin envelopes with 20% and 40% WWR and three multi-skin envelopes with 80% WWR for the interior skin and a fully glazing external skin applied in different cavity depths. Biophilic and thermal performance of the envelopes are evaluated through developing numerical models of an open-plan office in Northern Canada, as a case study. Healthy lighting performance of the envelopes are evaluated through developing an experimental setup with 1:50 scale models under actual clear skies combined with numerical models of the office. The results reveal that multi-skin envelopes have promising potentials to promote biophilic, healthy lighting and thermal performance in sub-Arctic climates. However, such envelopes must be further developed by combining with adaptive insulated shading devices for higher lighting and thermal performance.

A2.2 Introduction

This research explores the performance of single-skin and multi-skin building envelopes under extreme sub-Arctic climatic conditions in terms of biophilic, healthy lighting and thermal indicators. Building envelopes in sub-Arctic climates, i.e., near and above 50° N towards the Arctic, must respond to biophilic, healthy lighting and thermal energy-efficiency factors in relation to the extreme cold weather and drastic seasonal day/night cycles. Envelopes' configuration and openings are main elements connecting indoors to outdoors which affect view and accessibility to the outdoor nature, daylighting, and day/night cycle, known as photoperiods [263]. Relationships with natural phenomena and the outdoor nature, identified as biophilia, are a contributing factor to building occupants' psychological wellbeing such as reducing stress and anxiety and improving cognitive performance [1, 3, 6]. Maximizing the use of daylighting and providing a proper lighting quality and sufficient darkness at the proper time of the day also contribute to occupants' photobiological wellbeing in terms of image-forming (IF) and non-image forming (NIF) responses [12, 262]. IF responses affect vision and visual performance. NIF responses regulate internal body clocks, wake-sleep cycles, alertness, and mood [65, 262]. Envelopes and openings also play key roles in thermal performance and energy consumptions of buildings related to heating and cooling systems [149, 197]. Openings' characteristics and sizes have considerable impacts on building heat losses and solar heat gains. Northern Canada building codes and practices are mainly developed based on low window-to-wall ratios (WWR) to reduce heat losses from openings [136, 263]. Increasing the WWR of existing envelope practices could elevate energy consumption of Northern buildings. Potentials of multi-skin envelopes to improve biophilic, lighting and thermal performance of Northern buildings have not, yet, studied. Previous research has mostly evaluated multi-skin building envelopes under temperate and hot climatic conditions in terms of visual comfort and daylighting and thermal performance [111, 197, 198, 323-325]. Biophilic and healthy lighting performance of multi-skin envelopes combined with thermal and energy-efficiency indicators under extreme sub-Arctic climatic conditions has not, yet, adequately studied [263].

This research evaluates biophilic, healthy lighting and thermal performance of five fundamental models of single-skin and multi-skin building envelopes with different window sizes under sub-Arctic climatic conditions of Northern Canada. Experimental and numerical methods were employed to evaluate the envelope models under actual and simulated Northern conditions. The results were discussed to provide a strategic overview for developing high-performance climate-responsive envelopes for Northern buildings which could promote biophilic qualities through efficient indoor-outdoor connections.

A2.3 Material and methods

Five fundamental envelope models applied to an open-plan office in Northern Canada were considered for performance evaluations. As depicted in Figure A2. 1, the proposed models include (1) a single-skin envelope with a low WWR of around 20%, as recommended by the national energy code of Canada for buildings [136, 271], (2) a single-skin envelope with an average WWR of around 40%, (3) a multi-skin envelope with a cavity depth of 40 cm and 80% WWR of internal skin, (4) a multi-skin envelope with an 80 cm intermediate space and 80% WWR of internal skin, similar to a covered corridor, and (5) a multi-skin envelope with a 200 cm intermediate space and 80% WWR of internal skin, as a habitable space similar to a covered balcony. A fully transparent single glazing skin is considered as the exterior skin of multi-skin envelopes.

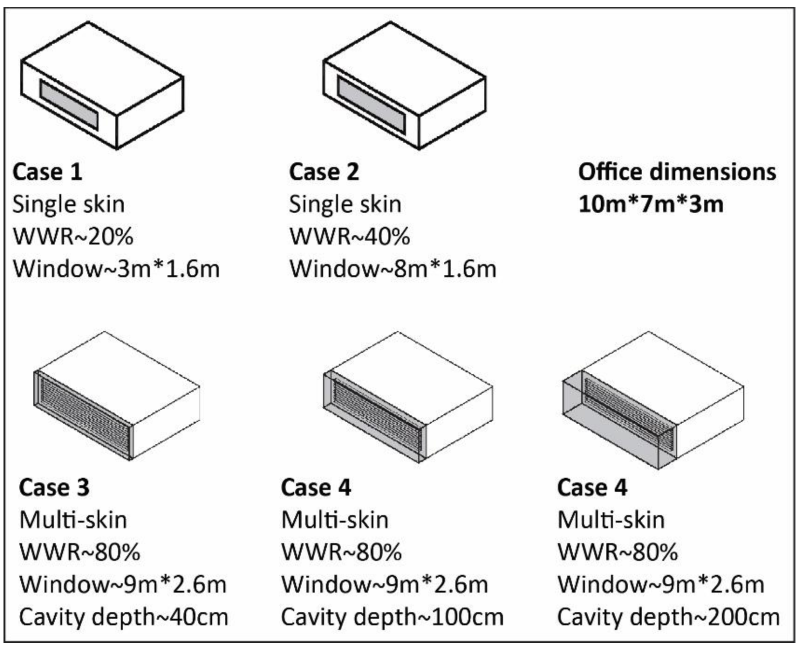

Figure A2. 1. The proposed envelopes for the reference office

Biophilic performance indicators are mainly related to connectivity and contact with nature, especially outdoor natural phenomena [1, 3, 6]. Biophilic performance is, therefore, represented by occupants' field of view (FOV) towards outdoors. Biophilic features of indoors, such as using greenery, are considered as a constant independent variable remained unchanged for all models. Biophilic performance of the proposed envelope models was evaluated by using numerical methods in Autodesk AutoCAD (2020) to calculate occupants' view angle towards the window and outdoors. Horizontal and vertical view angles of occupants in different viewpoints in the reference office, from the middle to sides and corners, were calculated. Vertical FOVs were calculated at the middle height of the space for all viewpoints (see Figure A2. 2). The overall FOVs were derived by multiplying horizontal and vertical view angles. FOVs were normalized in terms of human eyes' horizontal and vertical view angles corresponding to around 120°.

An experimental setup with 1:50 scale models of the open-plan office in different window sizes was developed to evaluate the healthy lighting performance under actual clear skies and direct sun lighting in Quebec, QC, Canada (Lat: 46° N, Long: 76° W). High dynamic range (HDR) imagery and post-processing techniques were employed to capture and compute healthy lighting parameters inside the models. Healthy lighting parameters are mainly related to photopic and melanopic units and colour temperature of lighting in the space. Photopic units represent potential IF responses. Melanopic units and colour temperature represent potential NIF responses [216, 283]. A proper lighting quality in terms of photopic and melanopic units and colour temperatures must be provided at different times of the day from the morning to evening [283]. Lighting with high melanopic units and colour temperature is, generally, recommended for the morning until noon. Lighting with low melanopic units and colour temperatures are, generally, recommended for the afternoon and evening. Complete darkness must be provided for nights and sleeping [262, 263]. The details of the experimental setup, HDR imagery, calibration and post processing were based on the previous studies of Jung and Inanici [216], Parsaee, et al. [283]. Photopic and melanopic units are normalized by the intensity of the photopic and melanopic luminance intensities of the exterior daylighting received at the vertical plan in the direction of the experimental set-up, i.e., towards the south. Furthermore, numerical models of the envelopes were developed by using an online tool offered by Marsh [311] to calculate spatial daylighting autonomy with a minimum threshold of 300 lux in the office, as an indicator of annual daylighting availability and penetration.

Numerical models were also developed in IES Virtual Environment Software [314] using the APACHE engine to evaluate thermal and energy performance of the envelopes in terms of heating loads. Heating loads were calculated for the energy required to provide occupants with acceptable thermal comfort zones and indoor air qualities inside the case study of the open-plan office in Kuujjuaq, Quebec, Canada (Lat: 58° N, Long: 68° W), as recommended by ASHRAE [121], NRC [136]. The details of the thermal model are offered in Table 1. Thermal performance of the envelopes was evaluated for applications on different façade directions by calculating heating loads of the office directed towards the south, east, west, and north.

Table A2. 1. Thermal model settings and characteristics[13]

Item	Value
R-value (efficient) of the opaque wall	3.85 (m^2K/W)
Roof and floor R-value (efficient)	5.03 (m^2K/W)
Double glazing window net U-value (including frame) applied to the exterior skin of cavity/intermediate space filled with Krypton	1.41 (m^2K/W)
Double glazing window, Outer pane transmittance	0.4
Double glazing window, Inner pane transmittance	0.78
Double glazing window SHGC	0.3856
Single glazing window net U-value (including frame) applied to the exterior skin of cavity/intermediate space	5.81 (m^2K/W)
Single glazing window visible light normal transmittance	0.78
Single glazing window SHGC	0.8116
Crack flow co-efficient for the single glazing window	0.15 (l/s/m/Pa^0.6)
Insulated panels R-value	2 (m^2K/W)
Heating set-point	21 °C
Heating set-back	18 °C
Opening setpoint for natural ventilation	21 °C (outdoor air temperature)
Office occupancy hours	08:00 - 18:00 of weekdays throughout the year
Occupancy density	14 (m^2/person)
People (latent and sensible heat)	150 (W/person)
Lighting	12.00 (W/m^2)
Computer and equipment	12.00 (W/m^2)
Infiltration rate of the interior space	0.35 ($l/s/m^2$)
Infiltration rate of the cavity/intermediate space	0.7 ($l/s/m^2$)
Auxiliary ventilation	8.5 (l/s/person)

A2.4 Results and discussions

The results are discussed in terms of biophilic, healthy lighting and thermal performance of proposed cases as the following sections.

A2.4.1 Biophilic performance of the envelopes

The envelope models proposed with higher WWRs, cases 2-5, are offered higher biophilic performance related to occupants FOVs to outdoors. As illustrated in Figure A2. 2, increasing the window size from 20% to 80% increases occupants' overall FOV from nearly 2% to 10% for

[13] *The table is revised to use in the thesis based on the jury's comment.*

viewpoints near the back wall. The window size of 20% WWR, case 1, offers significantly obstructed views towards the outdoor, especially in terms of horizontal FOVs of occupants near the side walls and corners. Increasing the window size from around 40%, case 2, to 80%, cases 3-5, increases the individual's overall FOV about 20% to 50% at different viewpoints in the middle and corner of the space. The results also show that the window size of near and above 80% offers relatively immersive views to the outdoor nature, especially for the spots near the window. As biophilic design calling for immersive views to nature, window sizes of above 40% are recommended for higher biophilic qualities.

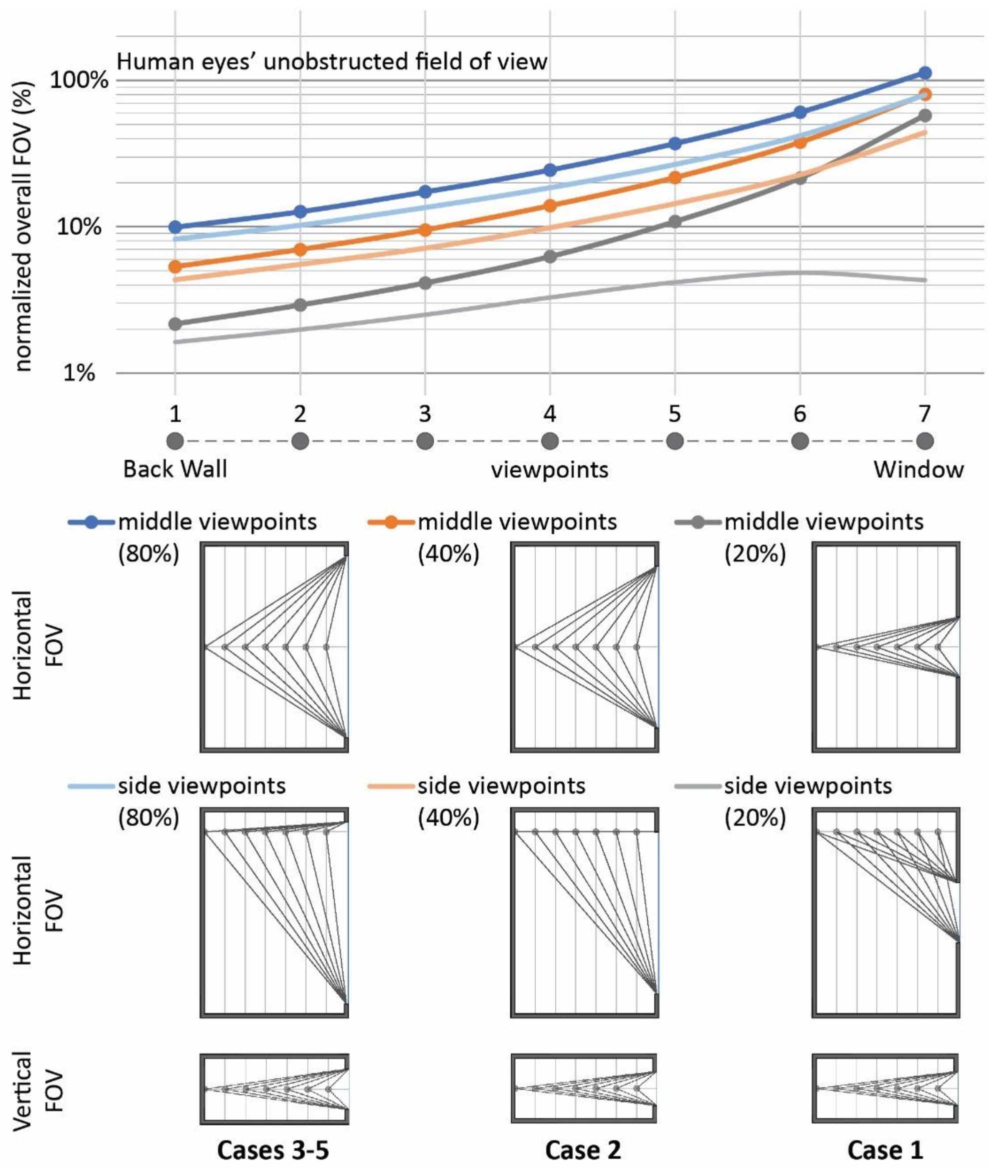

Figure A2. 2. Impacts of different window sizes on occupants' field of view (FOV) to outdoors at different viewpoints in the space

A2.4.2 Healthy lighting performance of the envelopes

The experimental results show the higher daylighting performance of envelopes with average and high window sizes, cases-2-5, in terms of the penetration, distribution and probabilities of photopic and melanopic units and colour temperatures inside the model. As illustrated in Figure A2. 3, increasing the window size from 20%, case 1, to 40% and 80%, cases 2-5, increases the frequency and probability of higher photopic and melanopic units in the space. The small size window of case 1 significantly obstructs daylighting penetration in the space. The normalized photopic and melanopic intestines are accumulated around 10% of the outdoor daylighting photopic and melanopic intensities. The probability of daylighting autonomy with above 300 lux in the space is less than 10% throughout the year (Figure A2. 3-d). Cases 2-5 with 40% and 80% WWRs enable daylighting to penetrate and distribute in the space. The frequencies of high photopic and melanopic units are significantly increased compared to case 1. The normalized photopic intensity in case 2 is distributed mostly between 20% to 40% within the side viewpoint and between 25% to 50% within the back viewpoint, which is significantly higher than the corresponding values for the case 1, i.e. 10%. In cases 3-5, the normalized photopic intensity is distributed between 30% to 60% within the side viewpoint and between 35% to 70% within the back viewpoint which is higher the case 2 and also the corresponding values for the case 1, i.e. 10%. The probability of daylighting autonomy with above 300 lux accounts for at least 20% of the space for cases 2-5 which is twice the corresponding value for case 1, i.e. less than 10%. Daylighting penetration in the space is highly increased for cases 2-5 reaching the back wall compared to case 1. Overall, the higher window size offers higher daylighting accessibility in the space. However, larger window sizes increase the risk of glare in the space demanding efficient shading devices such as blinds, curtains, or shutters.

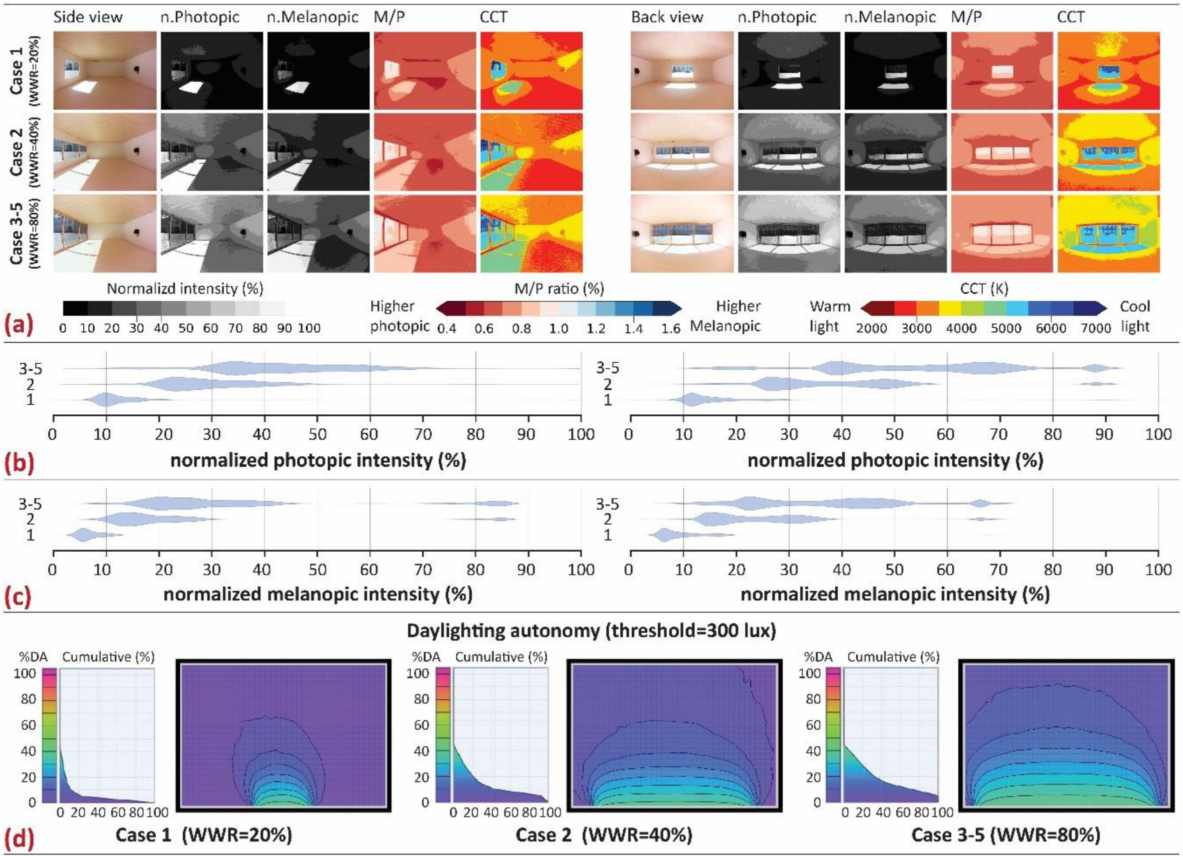

Figure A2. 3. Impacts of window sizes on healthy daylighting parameters and daylighting autonomy inside the office

A2.4.3 Thermal performance of the envelopes

The results reveal the high thermal performance of the multi-skin building envelopes under the south, west and east directions in the extreme cold climatic conditions of Northern Canada. As illustrated in Figure A2. 4, heating loads of the reference office with a single skin façade and 20% to 40% WWRs, cases 1-2, are almost around 200 kWh/m^2/yr under different directions. Applying a multi-skin envelope with 80% WWR and different cavity depths from 40 cm to 200 cm, cases 3-5, considerably reduces heating loads of the office by around 40 kWh/m^2/yr under the south direction. This is mainly related to higher potentials of solar heat gains enabled by larger window sizes. Heating loads of the office with the multi-skin envelopes and the huge window size, cases 3-5, are almost similar to heating loads of the office with the single-skin envelopes and small-average window sizes, cases 1-2. However, the multi-skin envelopes increase the heating loads of the office about 20 kWh/m^2/yr under the north direction compared to the corresponding heating loads for the single-skin envelope offices. This is mainly related to higher heat losses from the high WWR of the proposed cases under the north direction where solar radiations are negligible. Note that cooling systems are not required in such extreme cold climates where opening the window for a few hours of natural ventilation could fulfil potential cooling demands in the summer. No overheating has also occurred inside the cavity.

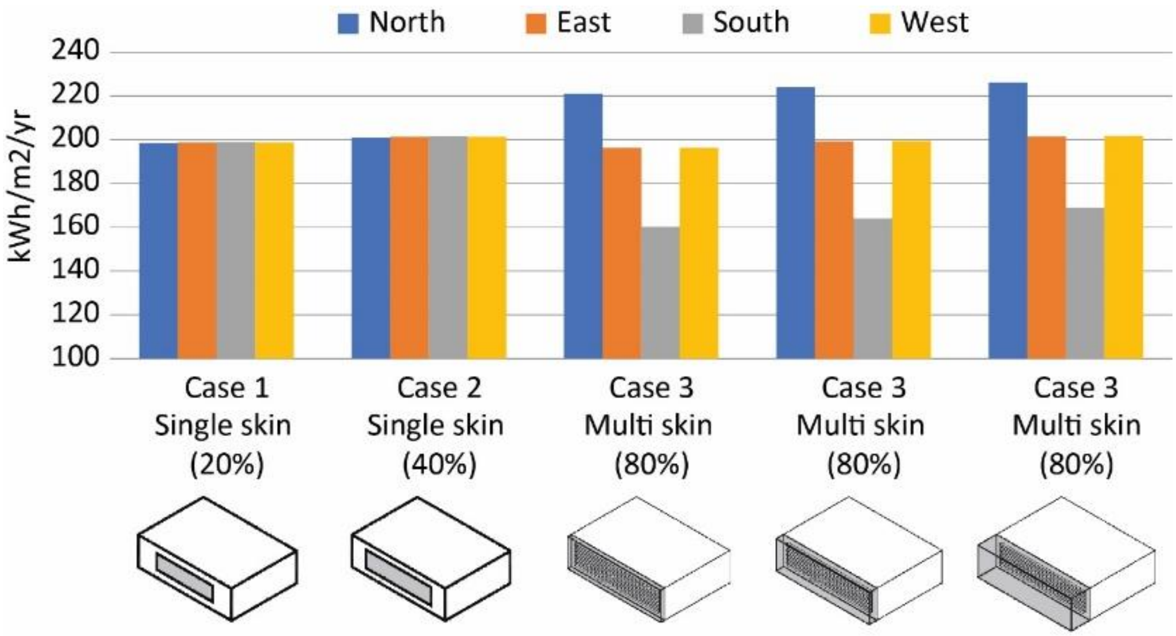

Figure A2. 4. Annual heating loads of the reference office proposed with different envelope configurations and WWRs under various directions in Kuujjuaq, Quebec, Canada.

A2.5 Conclusions

This research studied biophilic, healthy lighting and thermal performance of different single-skin and multi-skin envelopes under extreme sub-Arctic climatic conditions of Northern Canada. The results of research revealed the promising potentials of multi-skin envelopes with high WWRs to establish efficient indoor-outdoor connections offering higher biophilic, daylighting and thermal performance. Single-skin envelopes with the small opening size, as recommended by Canada building and energy codes, present very poor performance in responding to biophilic and healthy lighting requirements. Yet, higher window size increases the risk of glare and visual discomfort which demands efficient shading devices to control daylighting intensity. Shading devices are, generally, required for all envelopes with high or low window sizes to control the low-altitude sun lighting in Northern latitudes as well as to block daylighting during the long days of the summer. Future research must develop multi-skin envelopes with effective shading devices to improve the overall performance of the building in terms of biophilic, health lighting and thermal indicators. Multi-skin envelopes with habitable or transient intermediate spaces such as corridors and balconies must be further developed which could improve biophilic qualities of Northern buildings. Such spaces could, also, be developed as a cultivating area similar to greenhouses for Northern buildings. Adaptive shading panels with dynamic behaviours made of (super-) insulation materials could be developed to modify daylighting parameters related to occupants' photobiological needs as well as to cover openings and reduce heat losses when daylighting and views to outdoors are not required for the interior, for example during night times or weekends in the case of offices. The configurations and material of the external skin of multi-skin envelopes must also be further studied for extreme conditions of sub-Arctic climates.

A2.6 Acknowledgements

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