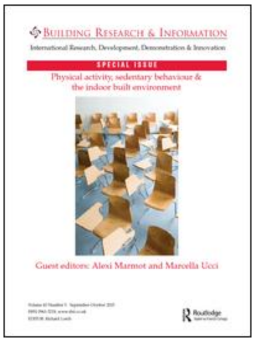

Building Research & Information

ISSN: 0961-3218 (Print) 1466-4321 (Online) Journal homepage: http://www.tandfonline.com/loi/rbri20

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To cite this article: Aylin Ozkan, Ted Kesik, Ayse Zerrin Yilmaz & William O'Brien (2018): Development and visualization of time-based building energy performance metrics, Building Research & Information, DOI: 10.1080/09613218.2018.1451959

To link to this article: https://doi.org/10.1080/09613218.2018.1451959

Published online: 11 Apr 2018.

BRI BUILDING RESEARCH & INFORMATION
2018
https://doi.org/10.1080/09613218.2018.1451959

Routledge Taylor & Francis Group

RESEARCH PAPER

Development and visualization of time-based building energy performance metrics

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ABSTRACT

In the face of climate change, and as building codes and standards evolve to promote increased building energy efficiency and reduced carbon footprints, it is also important to ensure that buildings, especially housing, can withstand prolonged power outages during extended periods of both extreme cold and hot weather to provide habitable shelter passively. This paper examines an approach for visualizing the impact of robust passive measures in multi-unit residential buildings by examining the 'weakest links in the chain' – the suites most susceptible to underperforming – in three climatic zones: Toronto and Vancouver, Canada; and Adana, Turkey. Two time-based and thermal comfort-related metrics are explored: thermal autonomy, a measure of what fraction of the time a building can deliver comfort without supplemental active systems; and passive survivability (also termed thermal resilience), a measure of the length of time a building remains habitable following the onset of a prolonged power outage during a period of extended extreme weather. A visualization of the results of parametric building energy simulations helps guide the selection of passive architectural parameters at the early stages of design to promote enhanced environmental performance and resilience.

KEYWORDS

adaptation; building performance; climate change; heat stress; passive performance; resilience; simulation; thermal autonomy; thermal resilience; time-based metrics

Introduction

It is widely acknowledged that architects and building designers seldom use building performance-simulation tools at the early design stage to inform their building designs (Hemsath, 2013). Even though decisions at the early stages of design have the largest impact on energy and cost (Hensen & Lamberts, 2011), current design practices tend to leave energy-reduction strategies to the end of the process (Samuelson, Lantz, & Reinhart, 2012), when changes can be disruptive and costly (Attia, Gratia, De Herde, & Hensen, 2012). An underlying proposition of this paper is that in order for architects to achieve buildings that minimize environmental impacts and lifecycle costs, they must meaningfully engage the integrated design process at the earliest possible stages of design.

A review of the literature indicates the criticality of building performance simulation in early stage (conceptual) design. A large number of simulation tools are now available to inform the early stages of design, but methodologies and approaches to their deployment in the integrated design process have not been formalized (Østergård, Jensen, & Maagaard, 2016). It also remains unclear how to apply effectively the many sustainability and resilience metrics for buildings (Marjaba & Chidiac, 2016). Beyond energy performance considerations, thermal comfort standards related to free-running buildings that increasingly rely on robust passive measures are not fully mature and only beginning to address issues of climate change and resilience (Lomas & Giridharan, 2012). Many of the design strategies available to designers for future-proofing buildings have been identified and compared, but protocols for modelling passive measures and occupant behaviour remain to be refined (Coley, Kershaw, & Eames, 2012). It is beyond the scope of this paper to address all the emerging issues related to sustainability, resilience and comfort; instead, a manageable visualization approach that addresses the need for assessing performance at the conceptual design stage is explored.

The proposition underlying this paper reinforces a need for practical approaches and graphical feedback methods that integrate energy simulation into the early design stage of buildings within mainstream architectural practice. Building performance assessment methods require appropriate performance metrics and

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indicators for specific objectives (Samuelson, Claussnitzerb, Goyal, Chena, & Romo-Castilloa, 2016). The most commonly used energy performance metrics at the building level rely on energy use for space heating and cooling, and overall energy use (de Wilde & Coley, 2012). Also, several non-energy metrics have been studied to describe or consider building performance. These metrics mainly include comfort, health and satisfaction; economic efficiency, productivity and resource optimization; and building functionality and resiliency (Frankel, Edelson, & Colker, 2015). For example, one study revealed the resilience of passively cooled buildings is linked to their life expectancy, which decreases with heat gains and the warmth of the locality (Lomas & Ji, 2009). Also, the authors argue that resilience to climate change, susceptibility to internal heat gains and impact of future heatwaves should be an integral part of building design. In another study, adaptive comfort degree-days was developed as a temperature difference/time composite metric to assess better energy consumption under changing climate conditions. The aim of the metric is to provide designers the opportunity of reducing energy consumption while ensuring that thermal comfort is maintained by allowing buildings to operate in free-running mode rather than use mechanical systems for cooling and/or heating (McGilligan, Natarajan, & Nikolopoulou, 2011). Both studies extensively discuss the available guides and standards for defining thermal comfort criteria, and suggest relating interior comfort to outdoor temperatures directly.

Furthermore, a major problem with current simulation approaches is that most request extensive input data (Ochoa & Capeluto, 2009) and they provide vast quantities of data output (Attia, Hamdy, O'Brien, & Carlucci, 2013). For design teams, it is very important and helpful (better design and time-wise) to identify the useful information to extract from simulation output at the very beginning (Ulukavak Harputlugil, Hopfe, Struck, & Hensen, 2006), something that is currently unknown to most architects.

In view of the present reality, and in recognition of the primacy of early design decisions in the environmental performance of buildings, this paper focuses on the development of a practical simulation approach aided by visualization techniques. It is an approach that could enable building simulation tools to be used for simpler evaluations to inform passive systems integration and optimization in early design phases through the time-based metrics of thermal autonomy (TA) and passive survivability (PS).

Within this paper, TA is a measure of the fraction of time a building can passively maintain comfort conditions without active system energy inputs. PS is a measure of the duration of time that a building remains habitable following a power outage over an extended period of extreme weather (O'Brien & Bennet, 2016). (The term 'passive survivability' is sometimes referred to as 'thermal resilience' to distinguish it from non-thermal aspects of PS, such as rainwater harvesting or renewable energy generation.)

While it is recognized there are many studies that reveal the issues related to the building simulation process during the early design stages, there has been little emphasis on visualizing the thermal performance of buildings using time-based metrics to inform the early stage design process better. In the literature, PS is becoming an important resilience metric that considers power blackout times and the impact of climate change on the severity and duration of extreme weather events. This paper is derived from a long-term research study that examines the use of 'time' as a measure of performance by showing the patterns and degrees of TA for residential apartment suites in different climates. A significant conclusion of the study is that the visualization of time-based energy performance metrics is critical to informing the early stages of building design. This conclusion stems from a survey of building simulation users and architects to assess the effectiveness and utility of these time-based metrics.

Design profession survey

In earlier phases of the study supporting this paper, a survey was conducted to assess the effectiveness of visualizing the time-based metrics of TA and PS derived from building performance simulations. The results are presented in an earlier paper Ozkan, Kesik, & O'Brien (2017b). In that survey, a 35-question online survey was conducted using Google Forms. In total, 65 valid responses were collected from architects, engineers and educators from a population of approximately 500 individuals contacted by e-mail. Many of the questions were multiple-choice (*i.e.* select one or multiple, five-point Likert-type scale of *agree* to *disagree*, short answer, long answer). However, participants were allowed to add further information if they wished to share further insights. The survey questions were separated into five categories: background information; knowledge of common energy metrics; interpreting proposed TA graphs (see Figure 3 as an example); interpreting proposed PS graphs (see Figure 15 as an example); and general questions to have participants' suggestions for future work related to time-based metrics. The paper resulting from the study focused on how to visualize the analysis of robust passive measures using time-based metrics.

In summary, the responses of the participants in the survey indicated the following:

- TA graphs are intuitive and indicate how a building design might perform passively, independent from mechanical systems. Such graphs have temporal resolution that is sufficient to understand the building''s energy performance.
- Likewise, PS graphs are effective in visualizing building-level passive-design strategies and have a temporal resolution that is sufficient to understand the indoor comfort conditions during extended power system failures.
- PS graphs are also useful for improving resilient design decisions because they display information at a human scale with familiar metrics: time and temperature.
- One important observation was that at the early design stage, building performance simulation should focus on these visualization techniques and their associated metrics, and correlate these to the conventional measures for energy-use intensity (EUI) and compliance with code targets.

In practice, the use of TA and PS metrics at the early stages of design involve conducting simplified energy simulations in free-running mode so that individual and combinations of passive measures could be quickly assessed in terms of their effectiveness. Concurrently, the peak and annual space heating and cooling energy demands for supplementary active systems could provide more conventional energy performance metrics. Once a combination of passive measures is decided, more detailed energy modelling of active systems may be conducted with the knowledge that vital passive performance measures will not be traded off against active system components.

By focusing on passive measures and time-based performance metrics, it is believed design teams can achieve better architectural solutions to building performance through passive measures provided by strategies involving building form, orientation, fabric and fenestration.

Methods

In this paper, an approach is demonstrated for analysing robust passive measures for improving thermal comfort and resilience in multi-unit residential buildings (MURBs) by examining the 'weakest links in the chain' – the typical suites that are most susceptible to underperforming – in three climatic zones: – Toronto (Ontario) and Vancouver (British Columbia) in Canada, and Adana in Turkey. Similar to the approach taken in structural engineering design, only the critical apartments suites are examined since the remaining suites will exhibit better performance. While whole building system performance is also important, the rationale for the approach being presented in this paper is that the passive measures needed to achieve acceptable levels of TA and PS must be satisfied in critical suites before they are extended to the building as a whole. For additional detailed information about modelling assumptions and methods, see Ozkan, Kesik, & O'Brien (2016).

TA is a measure of the fraction of time a building can passively maintain comfort conditions without active system energy inputs. In equation form, it can be expressed as:

$$TA = \sum_{t=1}^{8760} \frac{[T_{op}(t) \geq T_{\min}] \wedge [T_{op}(t) \leq T_{\max}]}{8760} \quad (1)$$

where $T_{\text{op}}(t)$ is the indoor operative temperature at the tth hour of the 8760-h year; $T_{\min}$ is the lower comfort threshold for TA; and $T_{\max}$ is the maximum comfort threshold for TA.

TA demonstrates how architectural parameters, such as orientation, form, fabric, glazing, shading and natural ventilation, can be intelligently integrated to improve environmental performance.

PS is a measure of the duration of time that an indoor space remains habitable following a prolonged power outage over an extended period of extreme weather. (O'Brien & Bennet, 2016). It guides designers towards buildings that will be less susceptible to becoming uninhabitable in the event of extended power outages or other system failures during extreme weather periods.

To define the lower and upper comfort thresholds for TA, an extensive literature review was conducted for this study. The most common comfort metrics in the literature (predicted mean vote – PMV; and predicted percentage dissatisfied – PPD) are derived from Ole Fanger''s comfort model (Fanger, 1967). In this comfort model, a statistical probability of comfort is correlated to a range of temperatures and humidity for a given air speed, metabolism and clothing level. Rather than being used to explore occupant comfort, these metrics are more typically used to define thermostat setpoints in conditioned buildings (Levitt, Ubbelohde, Loisos, & Brown, 2013). On the other hand, occupants in naturally ventilated buildings experience an expanded sense of thermal comfort when they have access to operable windows. For this reason, the adaptive comfort model, based on American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55 (2010), may be employed to determine allowable indoor operative temperature thresholds for assessing only passive measures in naturally ventilated buildings. However, the allowable operative temperature limits may not be extrapolated beyond mean monthly outdoor dry-bulb temperatures above 33.5°C (92.3°F) and below 10°C (50°F) in that model. Since the mean monthly outdoor dry-bulb temperature would be less than 10°C (50°F) in Toronto and Vancouver in winter, this comfort model cannot be used for winter months in this study. On the other hand, a standard Memorandum HTM03-01 (Department of Health, 2007), which is concerned with 'specialist ventilation for healthcare premises', offers a range of acceptable internal dry-bulb temperatures, which are quoted as 18–28°C (64.4–82.4°F) 'over which the temperature may float'. Lomas and Ji (2009) argue that the HTM03-01 is incomplete in its discussion and recommendations with regard to the internal conditions to be achieved in naturally ventilated healthcare spaces, especially for identifying the risk of overheating in summer. They recommend Chartered Institution of Building Services Engineers (CIBSE) *Guide A* (CIBSE Environmental Design, 2006) for that purpose. For naturally ventilated buildings, *Guide A* notes that 'during warm summer weather 25°C (77°F) is an acceptable indoor operative temperature'. Since no more specific guidance for naturally conditioned spaces is currently available in the literature, comfort levels of 18 and 25°C (64.4 and 77°F) operative temperatures for TA analysis are employed in this study. At the same time, the exact threshold is not the focus. The relative performance of the designs may be evaluated by using any reasonable comfort range with the process suggested in this paper.

For PS, wider temperature thresholds are chosen since 'survivability' suggests marginally acceptable, or reasonably tolerable, temperatures (*i.e.* habitable). A comprehensive review on the effect of low temperatures on elderly morbidity (Collins, 1986) is used as the basis for the lower indoor operative temperature threshold of 15°C (59°F) for the heating period. The 30°C (86°F) upper threshold is consistent with other health standards (*e.g.* the National Health Service (NHS), 2015, used about 30°C as a daytime health warning trigger). More recent research indicates that 'passive habitability' in relation to overheating should be based on the wet-bulb globe temperature (WBGT) and predicted heat strain (PHS) indices (Holmes, Phillips, & Wilson, 2016). This approach predicts a 25% chance of severe heat stress at dry-bulb air temperatures lower than 30°C (86°F) when the relative humidity (RH) exceeds about 70%, unless there is adequate air movement, signalling the importance of natural ventilation. At this time, defining suitable and practically enforceable indoor heat thresholds remains problematic (Anderson, Carmichael, Murray, Dengel, & Swainson, 2013), hence the PS thresholds deployed in this paper may be considered to be reasonable and manageable until such time as better public health guidance becomes available.

In order to test the applicability of the proposed approach, three distinct climate zones are selected for use in the simulations: Toronto in Ontario, Canada (ASHRAE Climate Zone 6); Vancouver in British Columbia, Canada (ASHRAE Climate Zone 5); and Adana, Turkey (ASHRAE Climate Zone 3). Toronto has a semi-continental climate, with a warm, humid summer and a cold winter. The outside temperature does not usually go below −20°C (68°F) and the average winter temperature is −4.6°C (23.7°F). The climate of Vancouver is a moderate oceanic climate that is warm and temperate. The winter months are much rainier than the summer months, which are typically dry, often resulting in moderate drought conditions, usually in July and August. The average annual temperature is 9.9°C. Adana has a typical Mediterranean climate. Winters are mild and wet and summers are hot and dry. The average annual temperature is 19°C (66.2°F). Figure 1 compares the three climate zones.

In all three geographical locations, the predominant building type used for the construction of MURBs consists of a reinforced concrete frame where the shear walls are used to separate suites adjoining a double-loaded corridor or central core. Note that future proposed research, which is presently beyond the scope of the study supporting the findings of this paper, will examine wood-frame and mass-timber building typologies to assess the effects of lower thermal mass levels. The majority of suites have single-aspect facades, except for corner suites which have exterior walls on two sides, and are typically single storey. The provision of cantilevered balconies is optional and most of the buildings employ window-wall glazing systems with high window-to-wall ratios (WWRs > 80%). In this study, the average nominal size of a unit is considered as 70 m^2 with an aspect ratio of 2:1(width to depth). Unit heights are assumed to be 2.5 m including the 100 mm thickness of a single floor slab (*i.e.* half thickness for ceiling and half thickness for floor attributed to internalized units). The floor area of a unit is 64.8 m^2 and gross exterior wall area is 28.5 m^2. Units are located on intermediate floors with no heat transfer across the ceiling, floor or adjacent walls because the neighbouring units are assumed to be at a similar temperature and represent practically adiabatic boundaries. This simplifying assumption is reasonable because heat transfer through the envelope normally dominates over inter-suite heat transfer. Moreover, for the PS simulations, all neighbouring units are assumed to suffer the same failures, as

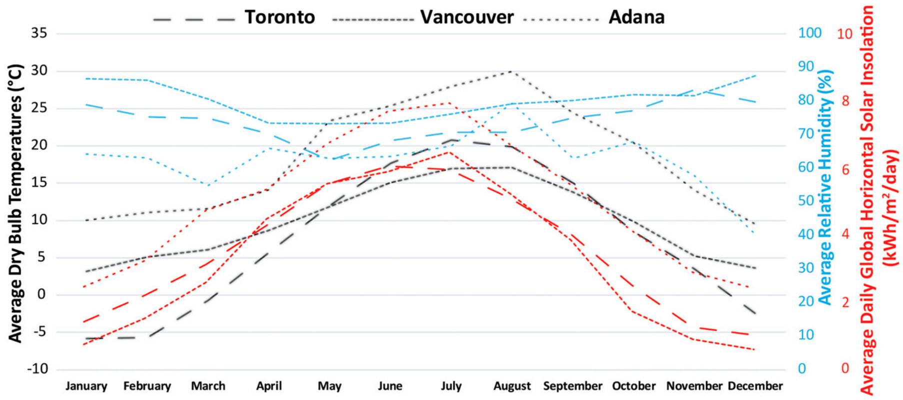

Figure 1. Comparison of dry-bulb temperature, relative humidity (RH) and solar radiation for Vancouver and Toronto, Canada, and Adana, Turkey.

would be the case for power failures and major mechanical equipment failures. The parameters set out in Table 1 were applied to a floor plate and exposed facade depicted in Figure 2.

The WWRs were selected such that normative fenestration practices in North American multi-unit residential housing determined the lower limit (40%), which then ranged up to practically an all-glazed facade (80%) in Toronto and Vancouver. In a hot climate such as Adana, since high solar exposure is not desirable, the lowest and highest limits were selected as 30% and 60% respectively. Exterior wall *U*-values begin with the minimum effective thermal resistance for opaque wall assemblies prescribed by applicable codes and standards and range down to a point after which sharply diminishing returns in energy conservation are observed. Window *U*-values and solar heat-gain coefficients reflect technologies that are currently available, again with the least efficient window assembly being prescribed by applicable codes and standards (all *U*-values are effective accounting for thermal bridging).

Custom occupancy schedules are also modelled based on different occupancy pattern in two countries. In Toronto and Vancouver, the predominant occupation of units occurs from 18.00 to 09.00 hours daily, whereas in Turkey, units are typically occupied all day and only the density of people changes at certain times of the day. Internal gains associated with occupancy do not significantly affect the simulation results, and while these are worthy of further exploration, in future work custom heating and cooling schedules for housing will not be deployed.

To validate the correlation of the time-based metrics with annual heating and cooling loads, simple heating, ventilation and air-conditioning (HVAC) systems are modelled using ideal loads, and energy consumption is calculated from loads using seasonal equipment efficiencies. A coefficient of performance (COP) of 1.0 for HVAC systems was used in order to estimate thermal demand without the influence of equipment efficiencies. Mechanical ventilation rates conform to minimum code requirements and for the initial purposes of this paper

Table 1. Parameters and corresponding values used to perform energy simulations.

			South, west, north, east		
Orientations			**Low WWR**	**High WWR**	
Window-to-wall ratio (WWR) (%)	Toronto, Vancouver		40	80	
	Adana[a]		30	60	
			Minimum requirements (MR)	**Better practices (BP)**	**High performance (HP)**
Wall	*U*-value (W/m^2.K)	Toronto	0.247	0.210	0.180
		Vancouver	0.278	0.210	0.180
		Adana	0.690	0.600	0.520
Glazing	*U*-value (W/m^2.K)	Toronto, Vancouver	2.500	1.700	1.000
	SHGC		High	Medium	Low
			0.45	0.35	0.25
	U-value (W/m^2.K)	Adana	2.700	1.700	1.000
	SHGC		High	Medium	Low
			0.53	0.47	0.3

Notes: [a]Excessive solar heat gains in the Adana, Turkey, climate zone demand smaller WWRs than Toronto and Vancouver in Canada.
The solar heat-gain coefficient (SHGC) corresponds to *U*-values of commercially available sealed glazing units for windows.

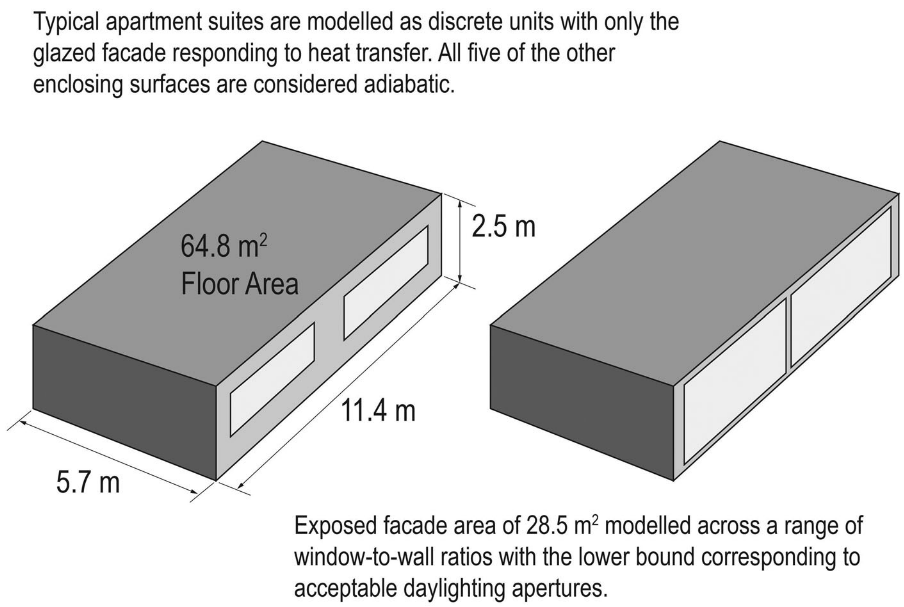

Figure 2. Characteristics of typical suites used in parametric simulations.

were not provided with heat recovery. Natural ventilation and infiltration airflow rates are calculated based on opening and crack sizes (medium), buoyancy and wind pressures. Annual average infiltration air change rate is 0.025 air changes per hour (ach) for default cases. When natural ventilation is provided, the air change rate reaches up to 0.67 ach. The EnergyPlus simulation engine was chosen for the study because it is a well-developed and well-documented, validated analysis tool widely used by researchers and practitioners. Also, the straightforward, user-friendly graphical interface DesignBuilder was used to perform 792 parametric simulations reliably and efficiently. For each unit configuration, based on four different orientations and two WWRs, three types of simulations are conducted to test 11 cases in all three climates. The three simulation types are defined as follows:

- Passive parameters are assessed through annual space heating and cooling EUI (kWh/m^{2}year). EUI herein refers to the space heating and cooling energy (with COP = 1) only.
- The systems for HVAC, lighting and equipment are turned off in the model for TA analysis. The number of hours above and below comfort levels of 18°C (64.4°F) and 25°C (77°F) are identified based on operative temperatures.
- For PS analysis, all active systems are shut off during a period of extreme summer or winter weather. The time between when heating is shut off and when the indoor operative temperature reaches 15°C (59°F) from an original heating setpoint of 21°C (70°F) represents the winter threshold for PS. In summer, the threshold is determined by the time until the indoor operative temperature reaches 30°C (86°F) from an original cooling setpoint of 25°C (77°F).

It is important to state a limitation in this study. Only indoor operative temperature is used to assess occupant comfort in order to determine how long a building can be passively self-sufficient in a year, thereby enabling designers to compare between alternatives in the early stages of design. It is recognized that indoor moisture (*e.g.* RH) will have a significant effect on occupant comfort. CIBSE *Guide A* (CIBSE Environmental Design, 2006) suggests that moisture may become apparent for sedentary, lightly clothed people as operative temperatures rise above 26–28°C (78.8–82.4°F): 'Thus, for most practical purposes, the influence of humidity on warmth in moderate thermal environments may be ignored.' However, recent work on overheating (Anderson et al., 2013; Holmes et al., 2016) points to the need to consider carefully temperature, humidity and air-velocity effects at the upper boundaries of the adaptive comfort zone. Future studies and users of the approach presented herein may choose to take into account the humidity or any other possible comfort criteria. The aim of the study underlying this paper is developing a manageable visualization approach for analysing robust passive measures through the time-based metrics of TA and PS.

The 11 passive strategies examined for each unit configuration are listed in Table 2. Envelope properties refers to the values stated in Table 1 for each climatic location.

Table 2. Passive measures applied in each of the 11 passive strategies examined.

	Envelope properties			SHGC				Balcony					Natural ventilation	
								Thermal						
Case	MR	BP	HP	High	Medium	Low	MIP (0.5 W/m^2.K)	Break	Bridge	Overhang	Enclosed	Shading devices: Auto sol-air	5%	20%
Base case	■			■										
1	■			+		–								
2	■			■			■							
3		■			■									
4			■			■								
5			■			■			■					
6			■			■		■		■				
7			■			■		■			■			
8			■			■						■		
9			■			■						■		■
10			■			■						■	■	

Notes: Envelope properties correspond to the wall and glazing values listed in Table 1 for each city.
MR = minimum required by the applicable building code; BP = better practice, typically midway between minimum requirements and high performance; HP = high performance, representing the best commercially available technology; MIP = movable insulation panels; auto sol-air = automatic shading device operation based on solar intensity and/or outside temperature; +/– indicates a higher solar heat-gain coefficient (SHGC) of 0.60 was applied to Vancouver and Toronto and a lower SHGC of 0.45 was applied to Adana for the minimum-efficiency windows.

For the base case, the minimum requirements (MR) according to applicable building codes are assessed. In case 1, for Toronto and Vancouver, a higher solar heat-gain coefficient (SHGC) of 0.60 is tested, while a lower SHGC of 0.45 is tested for Adana. In case 2, movable insulation panels (MIP) are operated only during winter nights and modelled as Venetian blinds with a *U*-value of 0.5 W/m^{2}K and zero airflow permeability. Case 3 considers a 'better practice' (BP) enclosure; case 4 moves to a 'high-performance' (HP) enclosure. In case 5, a cantilevered balcony slab with thermal bridge having an effective *U*-value of 3.4 W/m^{2}K is introduced along a strip of wall 0.2 m high running the length of the exterior of the suite. In case 6, a 2 m-deep balcony with a thermal break runs the entire length of the exterior wall of the unit acting as an overhanging shading device – it is assumed that the effective *U*-value of the wall is not affected by the cantilevered balcony slab due to the provision of a thermal break. In case 7, a 2 m-deep enclosed balcony is tested to analyze the buffer zone effect. In case 8, the operation of exterior shading devices is controlled based on outdoor air temperature and solar radiation striking the window (vertical blinds with high reflectivity slats for a west orientation, horizontal blinds for other orientations). Natural ventilation is provided through openings that are sized as 20% or 5% of the glazing area in cases 9 and 10 respectively. Activation of these operable openings assumes ideal operation by occupants when indoor operative temperatures are 23°C (73.4°F) or higher.

Unlike the apartments in Europe and Asia, operable windows are not necessarily a common feature in Canada. For this reason, considering the impact of operable windows on thermal comfort for highly glazed buildings is an important part of this study.

Analysis of thermal autonomy

First, modelling results are presented to illustrate the TA concept in each of the three climates. The TA metrics are then compared with EUI for a greater understanding and validation of this time-based metric.

Toronto, Ontario, Canada

For Toronto's climatic location, the effect of individual passive design strategies was discussed and visualized through TA graphs in a former paper by Ozkan et al. (2017b). In this paper, the subsequently improved graphs are used to demonstrate and summarize the output of simulations for the Toronto climatic location.

Figures 3 and 4 present the simulation results for a south-facing unit with an 80% and 40% WWR respectively. The HP envelope design having 5% of the glazing area fitted with operable openings, in combination with operable shading and natural ventilation strategies (case 10), delivers the best TA performance on an annual basis, 80% and 79% of the year in both south-facing units respectively. The reason the 80% WWR performs better than the 40% WWR is that while the smaller glazing area causes 60 h less overheating, it results in 150 h of less solar gains in winter. Overall, the results show that a smart combination of passive measures, such as HP envelope properties, operable shading and natural ventilation, can permit higher WWRs without significantly compromising TA. Another interesting observation is that having 20% of the glazing area fitted with operable openings enhances warm weather TA only marginally over the 5% operable openings case in Toronto.

Figure 5 illustrates the results corresponding to a north-facing unit with an 80% WWR. The HP enclosure delivers the best TA performance on an annual basis with an 80% of the fraction of acceptable hours in a south-facing unit, compared with 46% of the fraction of acceptable hours in a north-facing unit. An enclosed balcony with a thermal break performs better than a fully exposed balcony with a thermal break due to the former providing a buffer space and capturing heat gains in winter.

While not shown here, the results for the east- and west-facing units lie somewhere between the south- and north-facing cases. The relationship between the passive measures producing the highest level of TA remains consistent – an HP enclosure with operable shading and natural ventilation delivers the best performance in the Toronto climate zone.

Vancouver, British Columbia, Canada

In the analysis of TA, Figure 6 depicts results for a south-facing unit with an 80% WWR. If the unit assumes only the minimum envelope requirements, it is thermally autonomous for 20% of the year, whereas the HP envelope design, which has 5% of the glazing area fitted with operable openings, in combination with operable shading and natural ventilation strategies, delivers the best TA performance of 82% on an annual basis. The provision of thermal breaks at the cantilevered balcony slab improves overall acceptable hours slightly. A previous study reported that by reducing the heat transfer through balcony slabs, the space-heating energy consumption may be reduced by 5–13% and space cooling energy consumption by less than 1% (Ge, McClung, & Zhang, 2013). The smaller differences noted here, as compared with those reported in the literature, are due to assessing a significantly more thermally efficient enclosure.

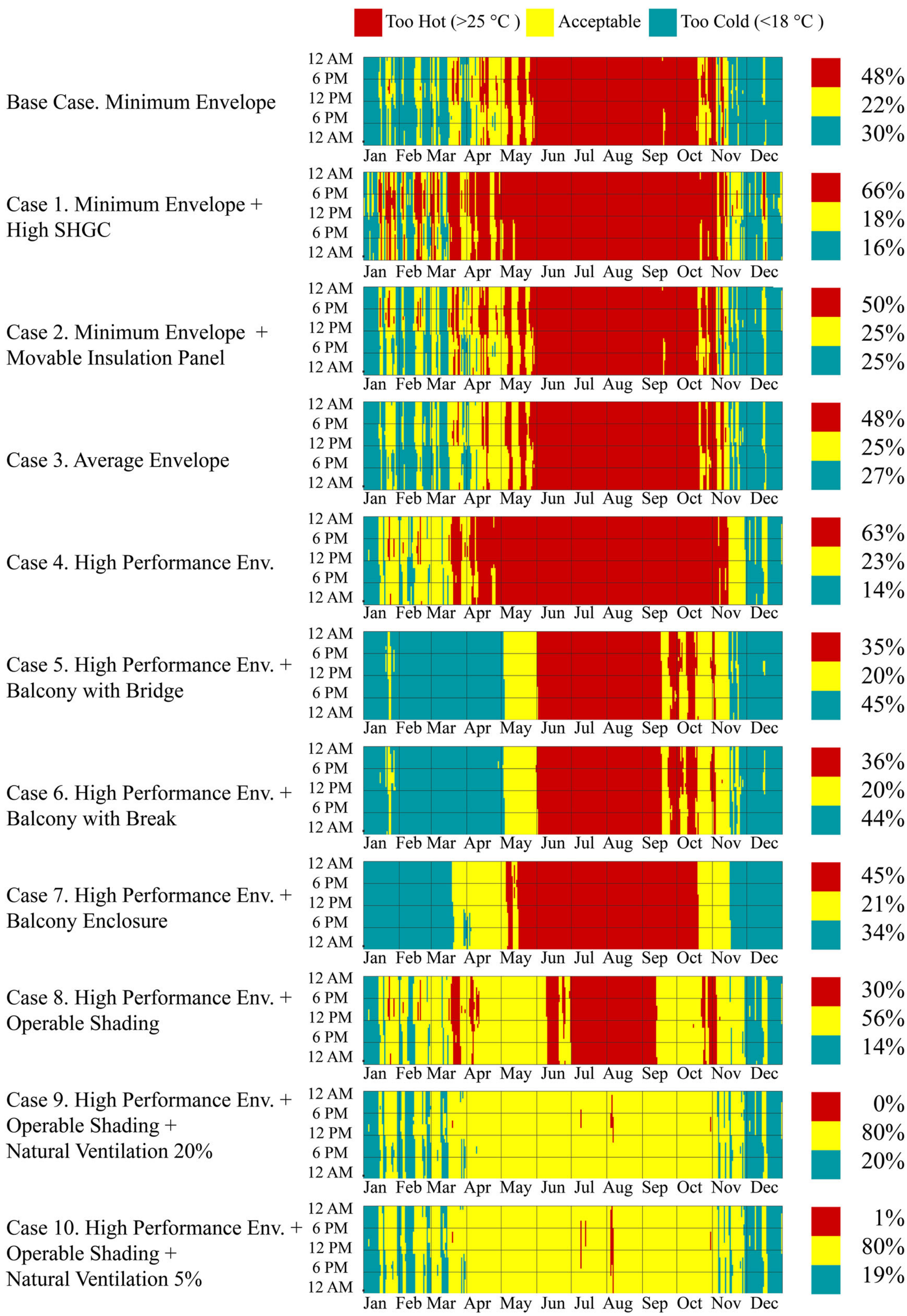

Figure 3. Thermal autonomy (TA) performance of a south-facing unit with an 80% window-to-wall ratio (WWR) in Toronto.

When the fixed shading devices (balconies) are exchanged for operable exterior shading devices, overall improvement is significant; thermal autonomous hours increase from 46% to 60%.

Figure 7 depicts results for a south-facing unit with a 40% WWR. On the whole, an HP envelope design which has 5% or 20% of the glazing area fitted with operable openings, and combined with operable shading and

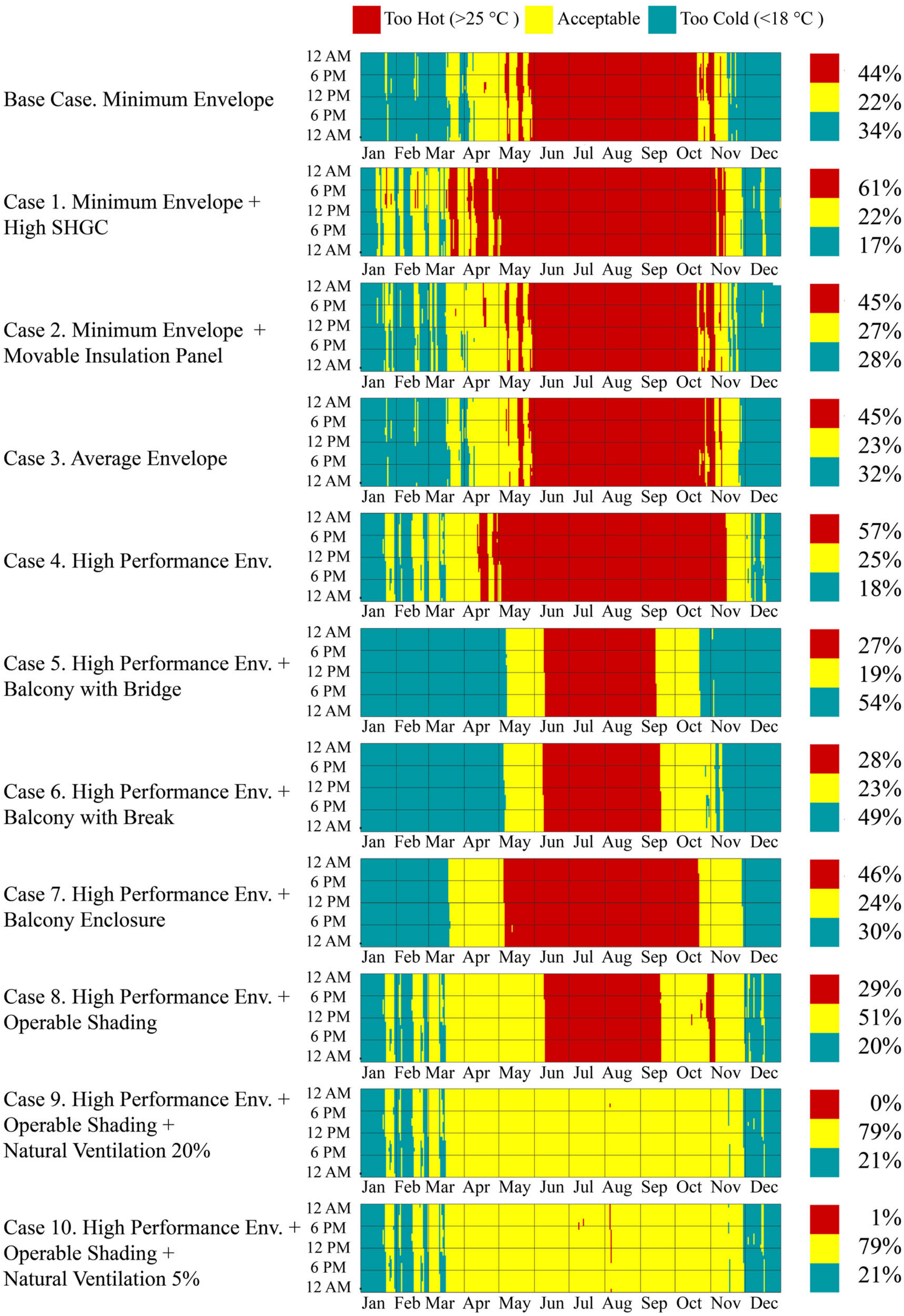

Figure 4. Thermal autonomy (TA) performance of a south-facing unit with a 40% window-to-wall ratio (WWR) in Toronto.

natural ventilation strategies, delivers the best TA performance of 89% on an annual basis. However, based on the EnergyPlus natural ventilation model, 5% operable openings provide as effective natural ventilation as 20% operable openings for a single aspect facade in Vancouver.

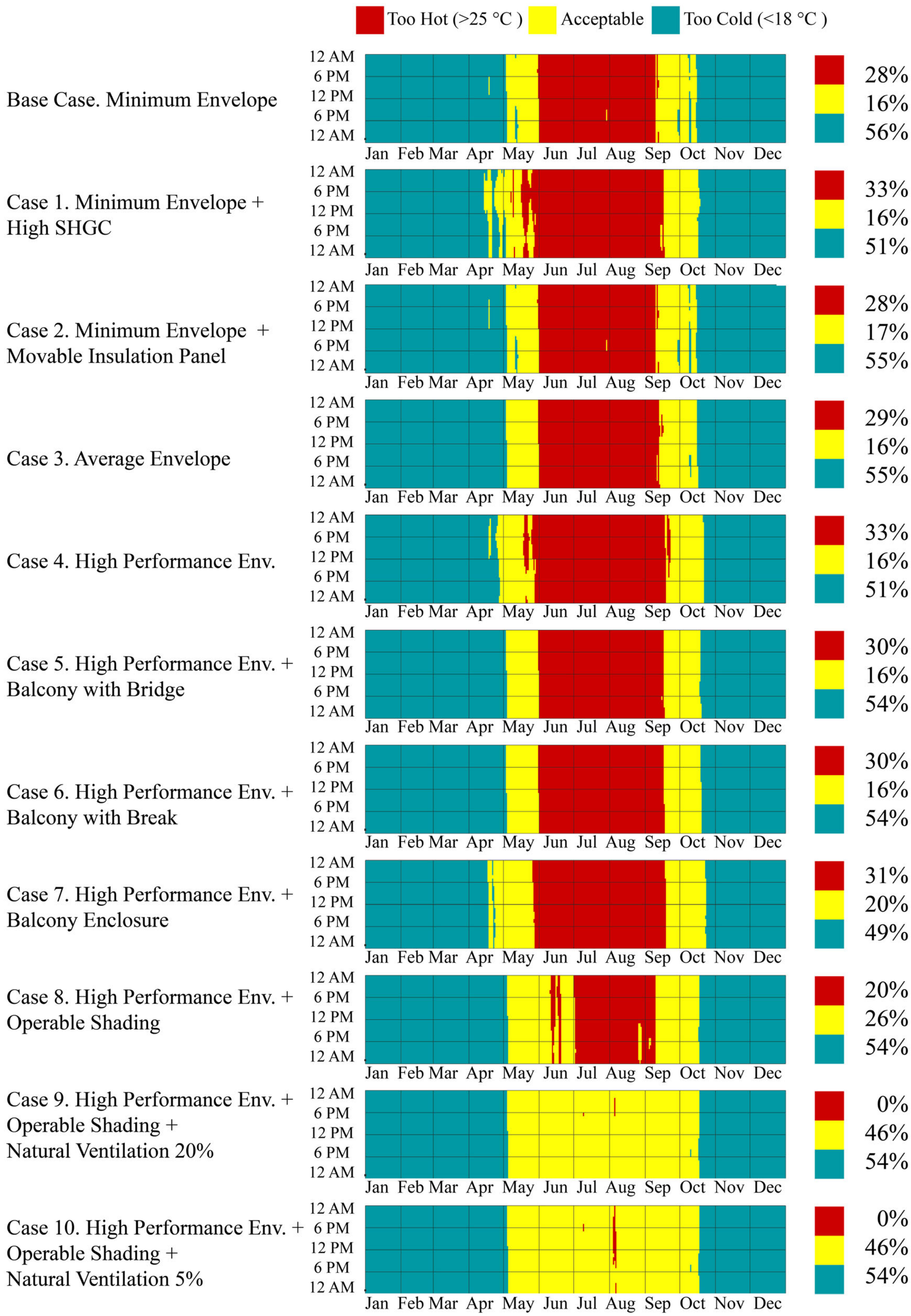

Figure 5. Thermal autonomy (TA) performance of a north-facing unit with an 80% window-to-wall ratio (WWR) in Toronto.

Figure 8 presents the simulation results for a north-facing unit with an 80% WWR. The difference between south- and north-facing units is very obvious when TA results are examined. The most HP enclosure delivers the highest degree of TA on an annual basis with the percentage acceptable hours of 82%

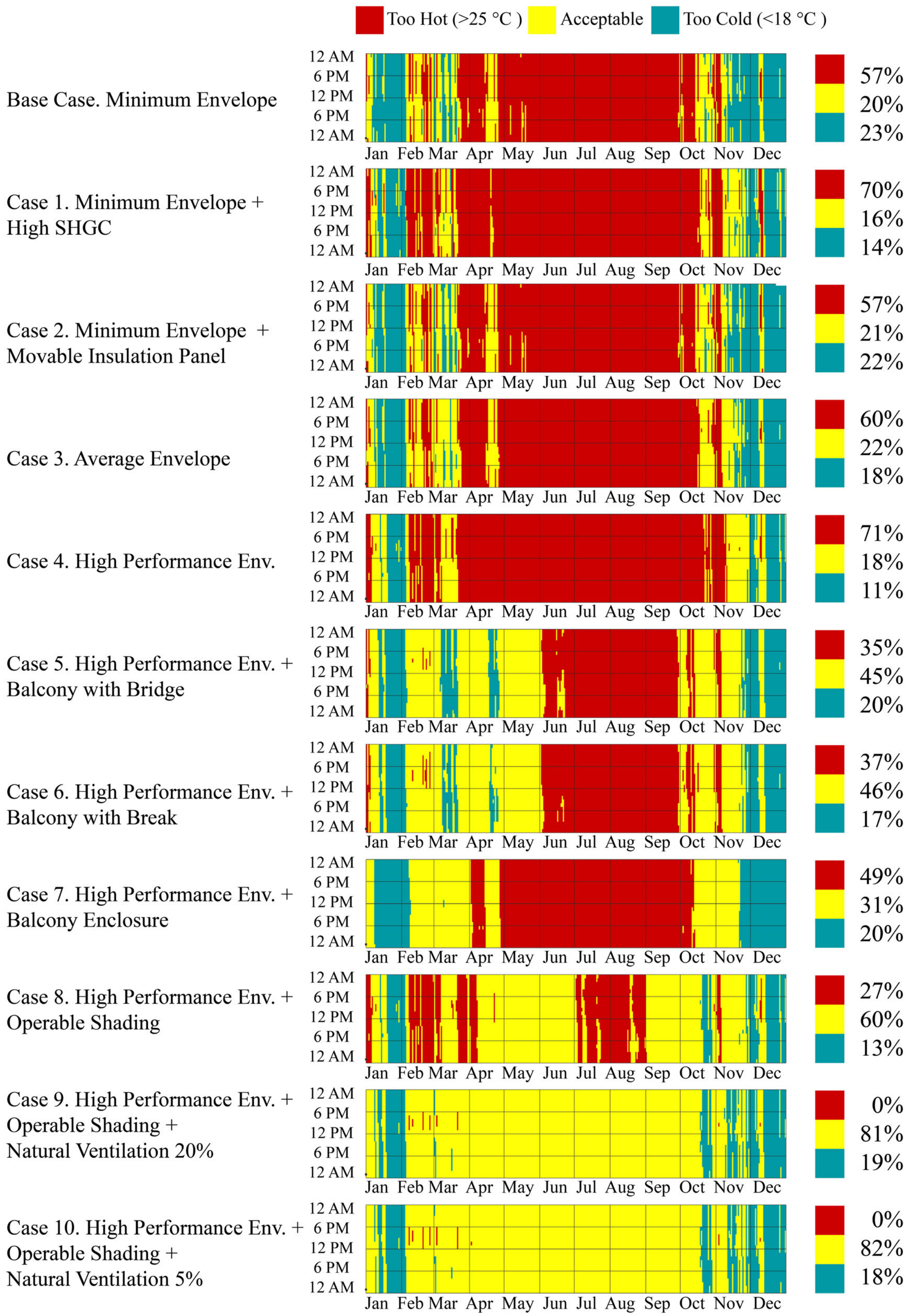

Figure 6. Thermal autonomy (TA) performance of a south-facing unit with an 80% window-to-wall ratio (WWR) in Vancouver.

in a south-facing unit (with an 80% WWR), whereas a TA of 44% is achieved in a north-facing unit. In summary, cold weather TA for north-facing units is more challenging and an approach combining an HP envelope and a shading device that incorporates thermal protection, such as enclosed balconies or

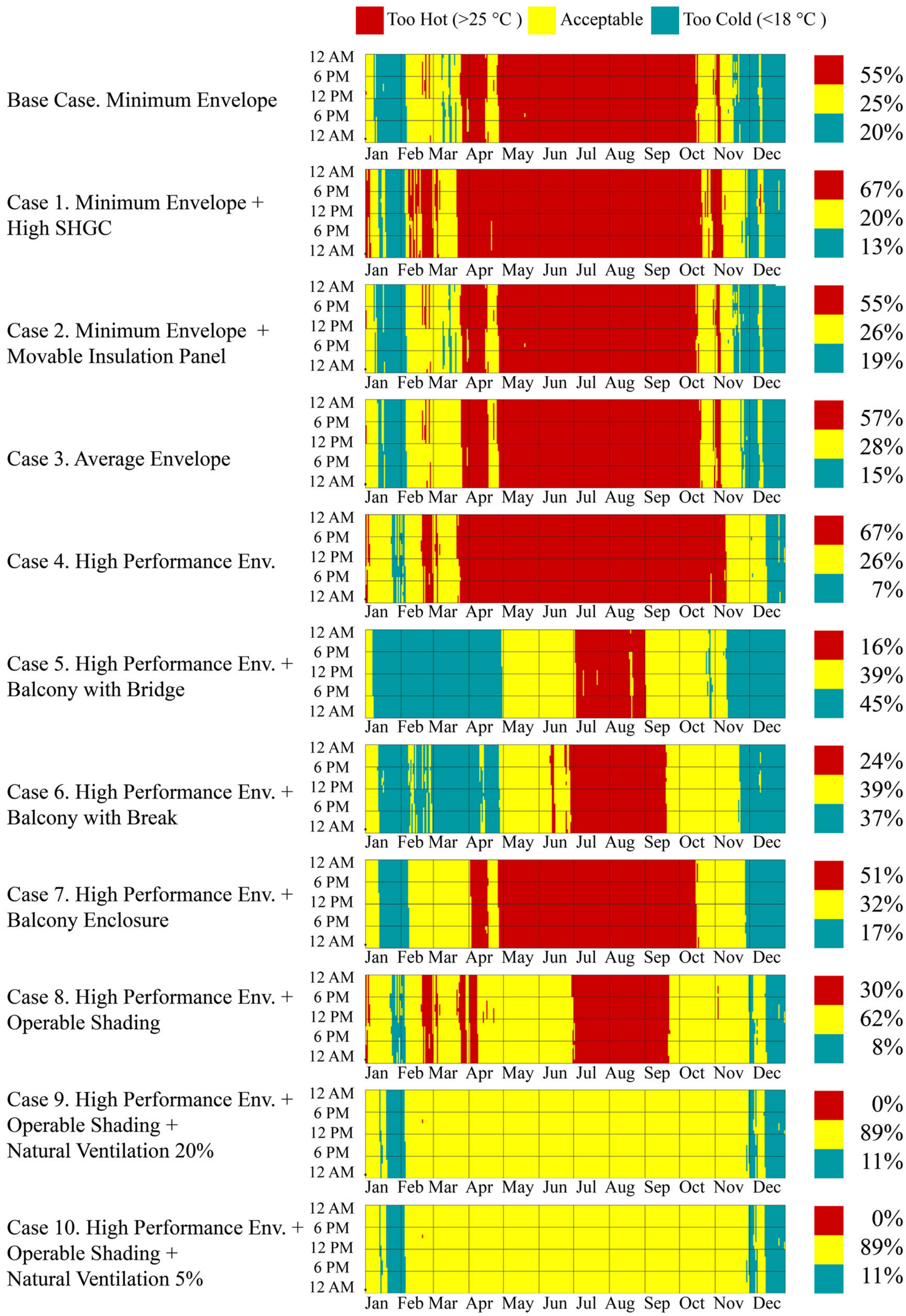

Figure 7. Thermal autonomy (TA) performance of a south-facing unit with a 40% window-to-wall ratio (WWR) in Vancouver.

MIP, may prove more effective. The effect of natural ventilation for north-facing units is negligible if operable shading (based on ideal operation by occupants) is deployed.

Adana, Turkey

In the analysis of TA, Figures 9 and 10 depict the results for a south-facing unit with 60% and 30%

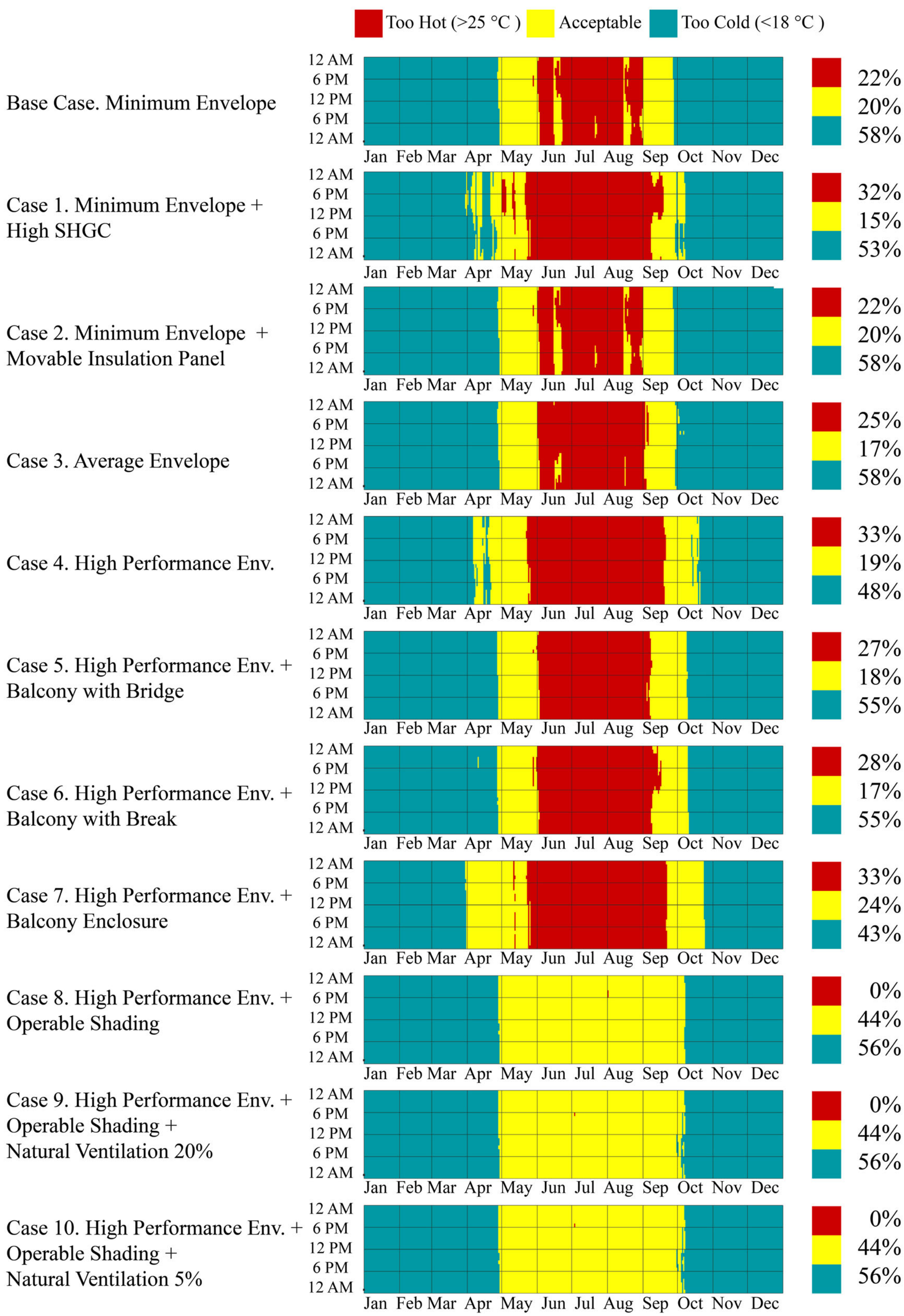

Figure 8. Thermal autonomy (TA) performance of a north-facing unit with an 80% window-to-wall ratio (WWR) in Vancouver.

WWR respectively. If the unit assumes only the minimum envelope requirements, without the provision of shading and natural ventilation, it is thermally autonomous for only 1% of the time during a year in both cases, where the average and HP envelope properties cannot improve the performance by themselves since the internal and solar heat gains are further trapped.

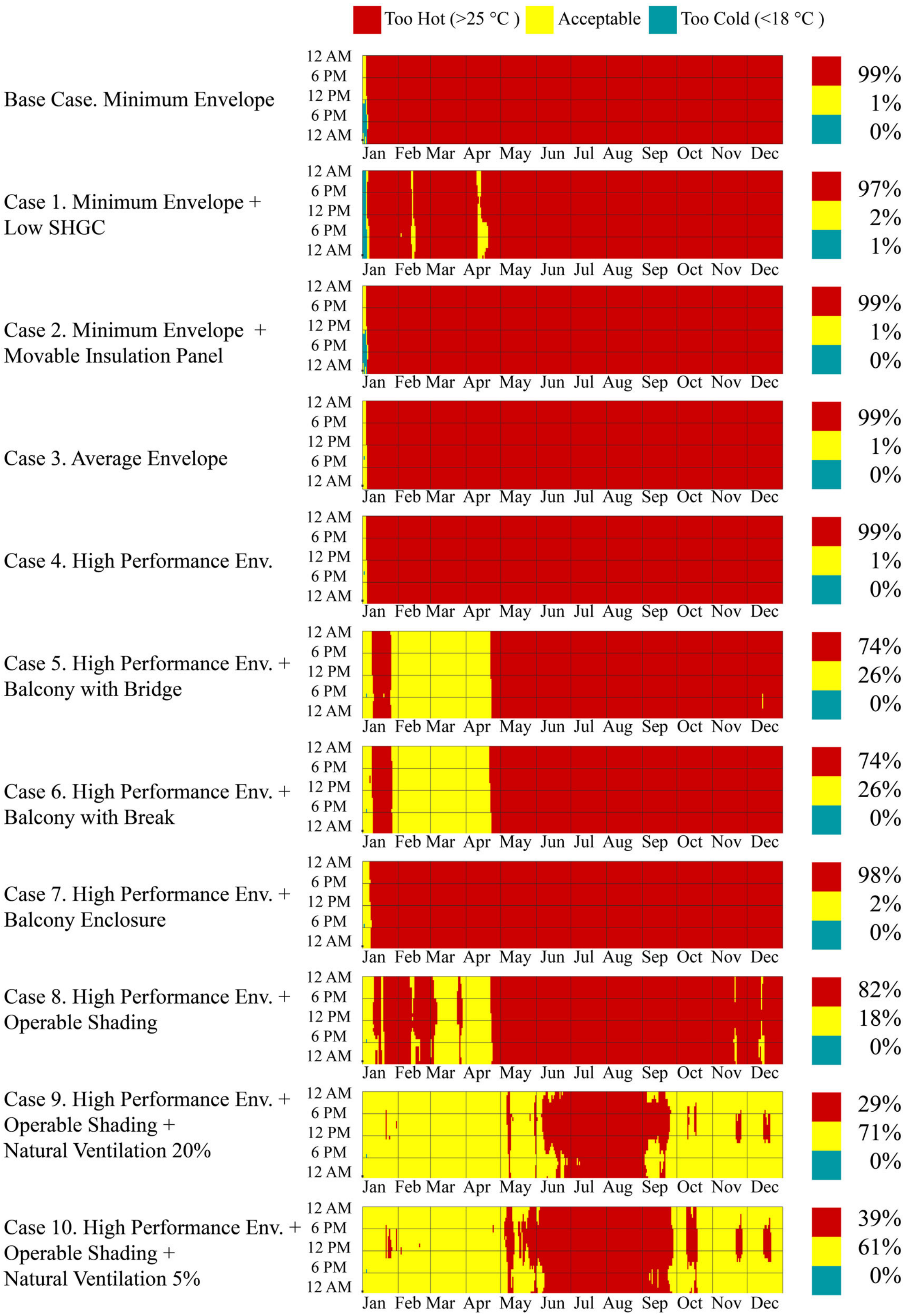

Figure 9. Thermal autonomy (TA) performance of a south-facing unit with a 60% window-to-wall ratio (WWR) in Adana.

Having a lower SHGC of glazing increases the percentage of acceptable hours to 2% in a unit with a 60% WWR, while the reduced SHGC combined with a 30% WWR reaches 5% of the fraction of acceptable hours.

Provision of balconies has a high shading effect for both WWR cases in south-facing units, but its impact is higher in a unit that has less glazing because the size of the balcony is sufficient to shade the smaller glazing

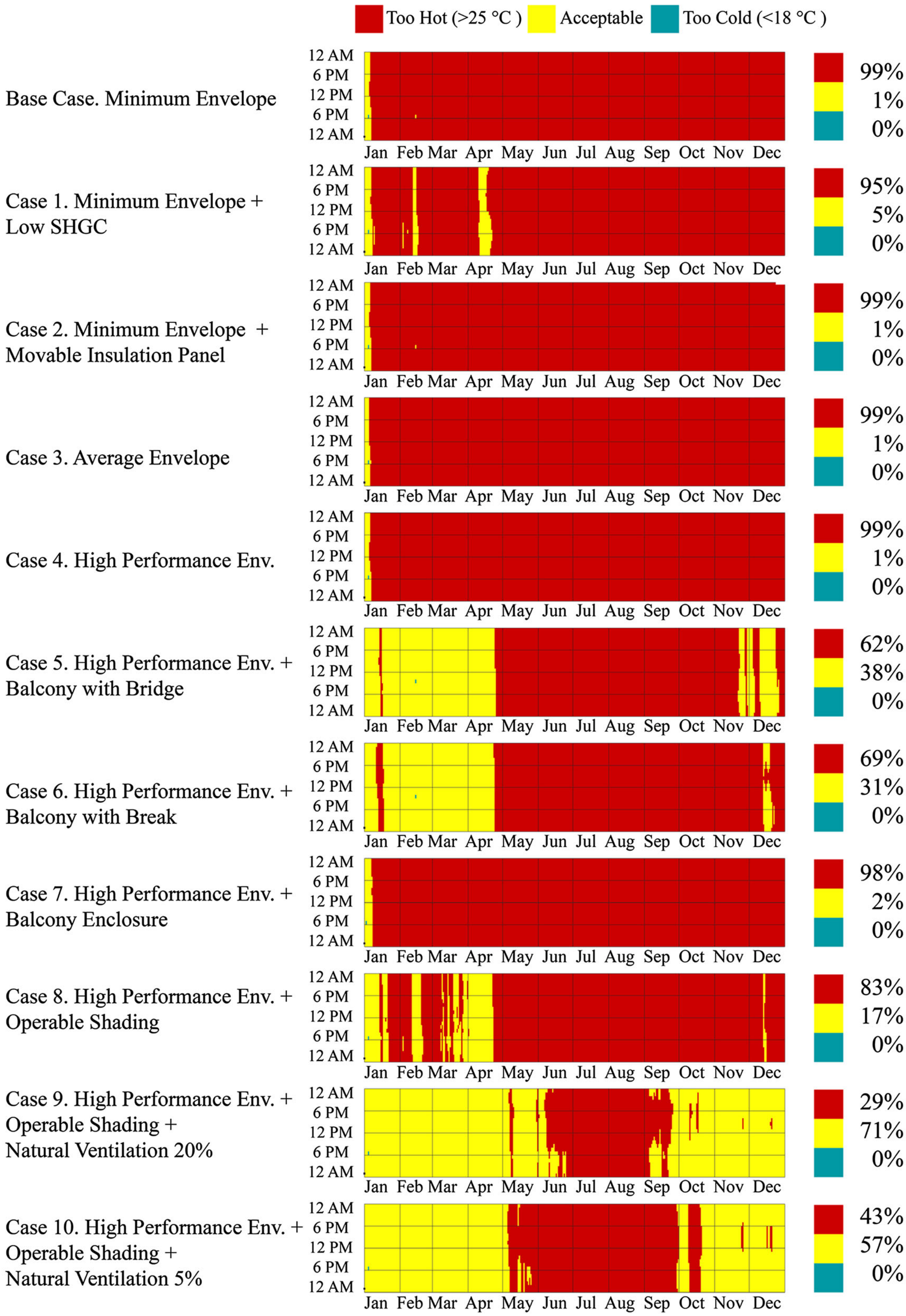

Figure 10. Thermal autonomy (TA) performance of a south-facing unit with a 30% window-to-wall ratio (WWR) in Adana.

area through a year. Note that thermal bridging across the cantilevered balcony slab has a beneficial cooling effect in a unit with a 30% WWR, but not in a unit with a 60% WWR. This indicates that only modest solar heat gains can be effectively dissipated through thermal bridging.

In the Adana climate zone, an enclosed balcony cannot be a reasonable option due to overheating from solar gains to the enclosed buffer space. Interestingly, an operable shading strategy does not deliver TA as effectively as a fully exposed balcony. This suggests large overhangs are better shading devices than exterior blinds, shades or louvres in this particular hot climatic location. However, when strategies are combined, the results show that an HP envelope design that has 20% of its glazing area fitted with operable openings, and combined with operable shading and natural ventilation strategies, delivers the best TA. For both the 60% and 30% WWR cases, acceptable hours of 71% on an annual basis are achieved using this combination of strategies. Note that, contrary to the Toronto and Vancouver climatic locations, in a cooling dominated climate such as Adana, the size of operable openings in the glazing area has a significant effect in reducing space cooling energy demands due to diurnal weather conditions that promote night cooling.

Figure 11 summarizes the results corresponding to the south-facing unit with a 60% WWR re-oriented to face north. Hot weather TA for north-facing units is still challenging, but it also becomes important to consider strategies for improving cold weather TA. Similar to the south-facing cases, when strategies are combined, the results show that an HP envelope design that has 20% of its glazing area fitted with operable openings, and combined with operable shading and natural ventilation strategies, delivers the best TA for north-facing units at 63%. Cold weather TA can be improved through the provision of enclosed balconies, but in order not to compromise hot weather TA, the balcony enclosure must be designed to open completely, effectively behaving like an unenclosed balcony as required.

Based on the analysis of TA for Adana's climate zone, it is observed that the thermal and optical characteristics of the envelope, including the WWR, are not as critical as the provision of effective shading and natural ventilation. This also means that opportunities for generous daylighting do not need to be compromised in order to achieve enhanced levels of TA.

Correlation of thermal autonomy with EUI

One question this study attempts to answer is the significance of TA as an indicator of energy performance. A former paper by Ozkan, Yilmaz, Kesik, & O'Brien (2017a) explored the relationship between EUI and TA (fraction of year). Here, a more extensive analysis and discussion are presented by comparing TA versus EUI for Toronto (Figure 12), Vancouver (Figure 13) and Adana (Figure 14).

A noteworthy result is that there seems to be some EUI threshold below which TA is greatly improved. It appears that the diminishing returns observed for measures such as increasing levels of thermal insulation are not similarly reflected in the relationship between TA and EUI below this threshold. This suggests that extremely low-energy buildings can have their energy balance critically impacted by ambient weather and occupancy phenomena that are relatively insignificant influences in less energy-efficient buildings. Further investigation is needed, but robust passive measures demonstrate significant TA benefits.

Overall, the data suggest that TA may be used as an approximate indicator of space heating and cooling energy demands at the early stages of design without the need for more sophisticated simulation models comprising active systems such as HVAC and lighting. The three climate types have similar correlations that resemble power-series models. The outliers are associated with cases where solar heat gains are not controlled. Assuming that the design of passive strategies would account for the management of excessive solar heat gains, then the correlation between TA and EUI becomes stronger.

Future research should investigate the relationship between TA and the space heating and cooling EUI for an entire building, not just individual suites. This will help even out the influence of solar gains associated with the various orientations on space heating and cooling energy demands. At this point it can be concluded that TA is strongly correlated to space heating and cooling EUI, and in general the higher the TA, the lower the EUI.

Analysis of passive survivability

PS, also referred to as thermal resilience, is a measure of how long inhabitants may remain in their dwellings during extreme weather events that coincide with extended power outages. Designs are typically evaluated with respect to their ability to maintain comfortable temperatures through entirely passive means during the outage. It is hypothesized that an apartment suite that is robust with regards to performance during regular operation will also be resilient (O'Brien & Bennet, 2016). In the current study, PS is assessed as a resiliency metric by shutting off all power to the apartment units (both HVAC and other energy-consuming equipment, appliances and fixtures) at typical summer and winter weeks which are selected from the entire typical year data in the EnergyPlus Weather (EPW) file. A simulation period was selected for three cities, via visual inspection, as the colder period during which the skies were mainly overcast and the warmer period during which skies are mostly clear. Future research should also focus on

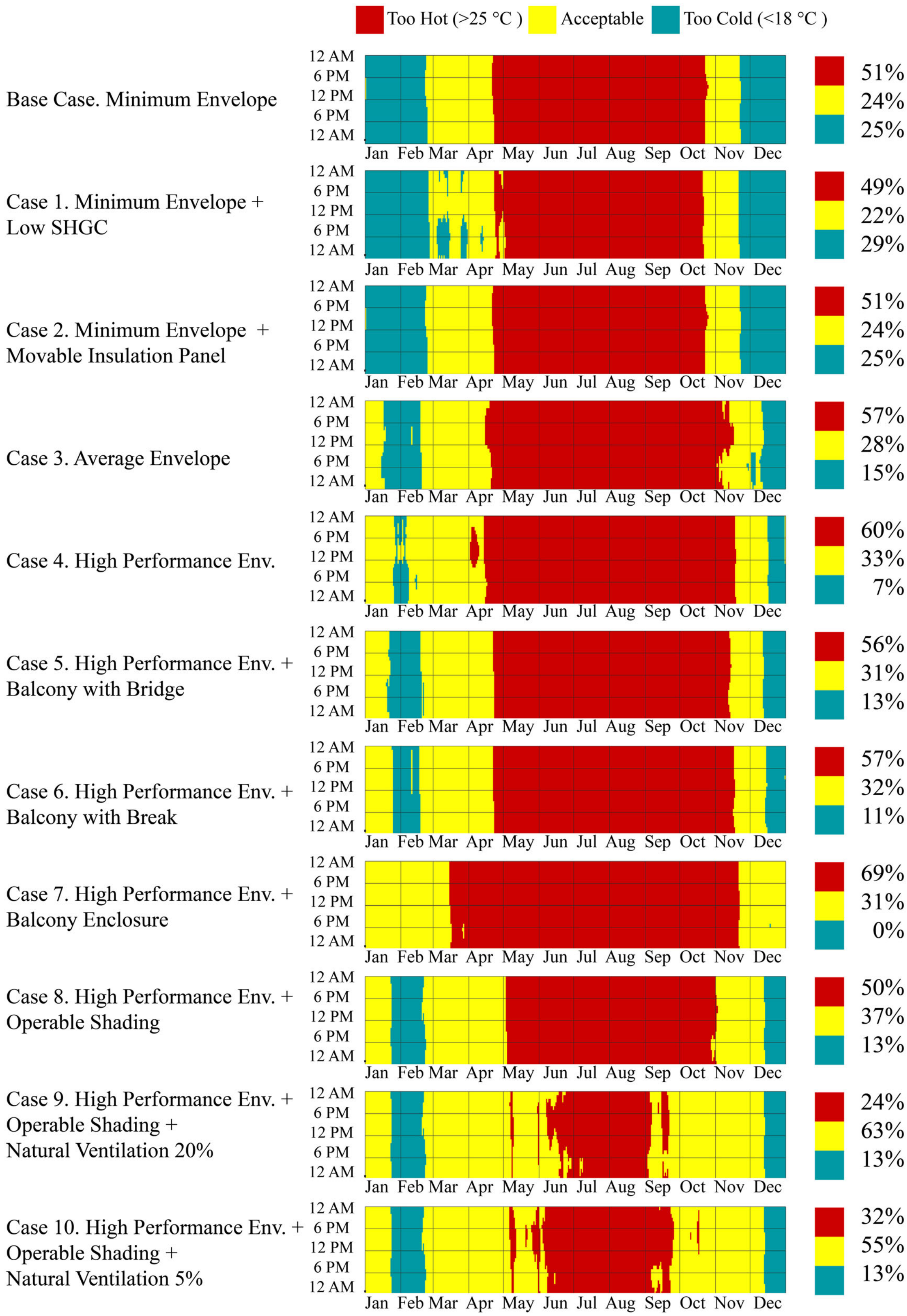

Figure 11. Thermal autonomy (TA) performance of a north-facing unit with a 60% window-to-wall ratio (WWR) in Adana.

applying the current metrics with weather files that incorporate the impacts of climate change on extreme weather events.

PS performance is depicted in Figures 15 and 16, which show south- and north-facing units with an 80% WWR in Toronto respectively. The indoor operative

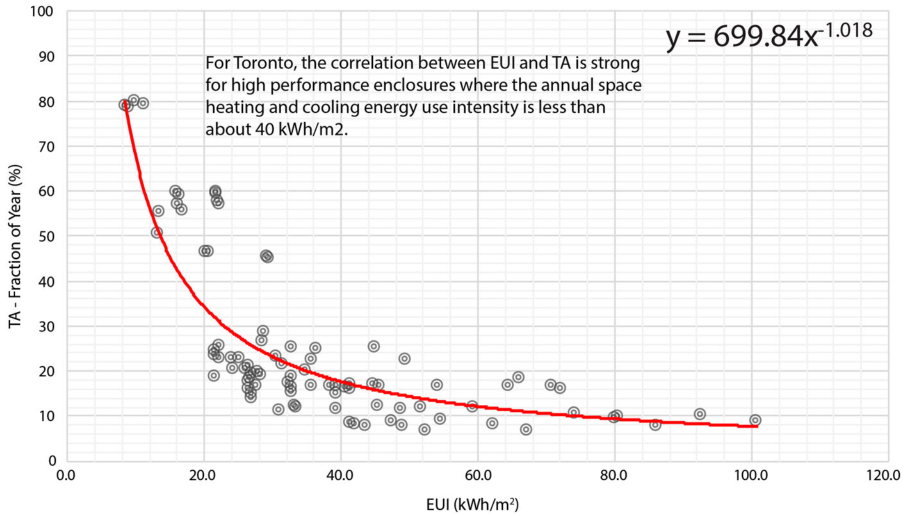

Figure 12. Correlation of space heating and cooling energy-use intensity (EUI) with thermal autonomy (TA) for all cases assessed in Toronto.

temperatures are tracked for eight days after the power failure in summer and winter, and indicate that designs with high TA also tend to have better PS. Selected PS results are also presented in a table format to illustrate the use of the approach and summarize the results for each climatic location.

Table 3 presents the time-based results in terms of the time between when heating/cooling is shut off on February 17/July 17 respectively and when the indoor operative temperature reaches 15°C (59°F) from an original heating setpoint of 21°C (70°F) in winter, and the time until the indoor operative temperature reaches 30°C (86°F) from an original cooling setpoint of 25°C (77°F) in summer. Table 3 lists the number of hours until the comfort threshold is exceeded and 'all' indicates acceptable conditions are maintained for the remainder of the analysis period, which is a month. Compared with TA analysis, wider temperature thresholds are chosen for PS analysis since 'survivability' suggests marginally acceptable temperatures.

Most cases with HP enclosures fare relatively well and maintain tolerable conditions for two to three days or longer. An important consideration is the required duration of PS and how it relates to recent events. For example, in August 2003, North America, including Toronto, experienced a massive blackout and it took nearly a week to restore power for many rural areas. Similarly, a summer flood and December ice storm both caused massive blackouts in 2013 in Toronto. Hurricane Sandy in 2012 also led to power

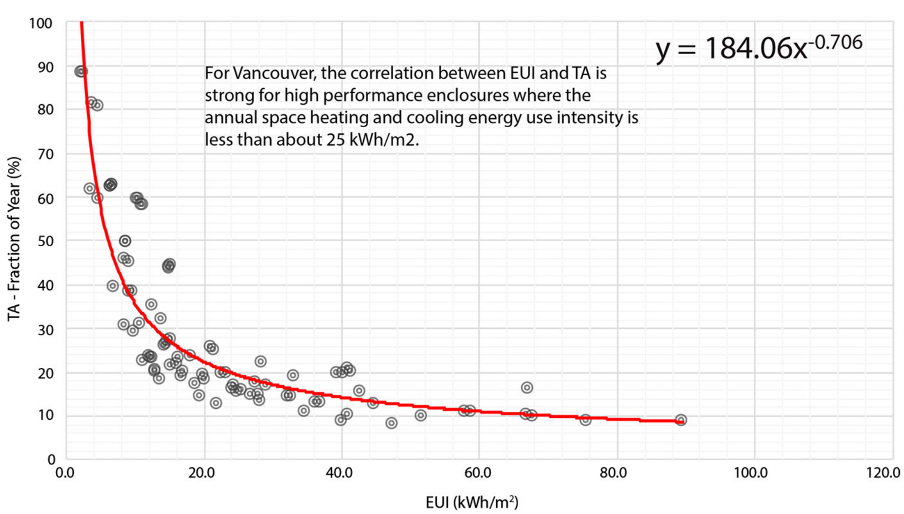

Figure 13. Correlation of space heating and cooling energy-use intensity (EUI) with thermal autonomy (TA) for all cases assessed in Vancouver.

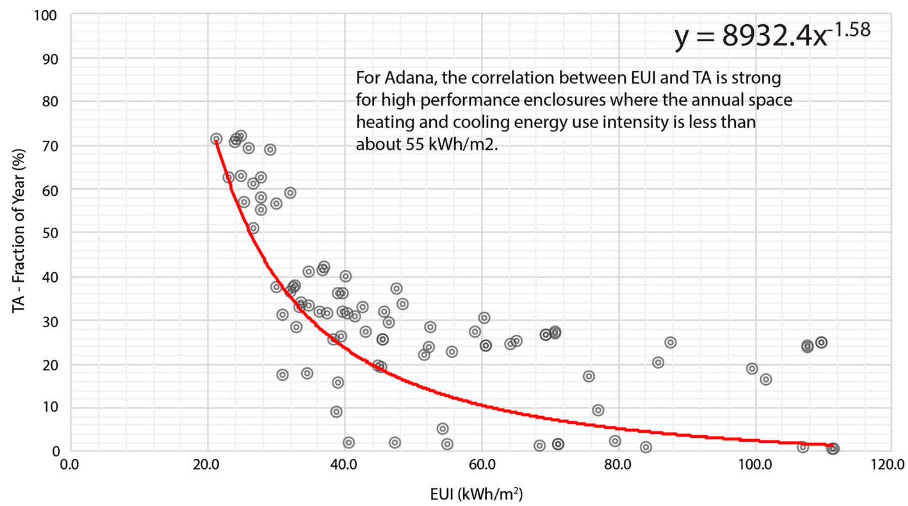

Figure 14. Correlation of space heating and cooling energy-use intensity (EUI) with thermal autonomy (TA) for all cases assessed in Adana.

outages for tens of thousands people in Toronto. Based on the analysis in this study, in the event of summertime power failure in all climates, occupants can maintain relatively comfortable temperatures through a combination of window openings and shading controls. The cases with large, unshaded windows are particularly vulnerable to overheating. In Toronto and Vancouver, in the event of a wintertime power failure, the HP envelope cases can maintain comfortable temperatures in all orientations except north. Enclosure properties (*U*-value and SHGC of glazing), followed by WWR, are the most effective parameters to achieve PS in a north-facing unit. In Adana, in the event of wintertime power failure, the indoor operative temperature never reaches below 15°C (59°F). It is likely that in such hot climates, the PS metric may only be

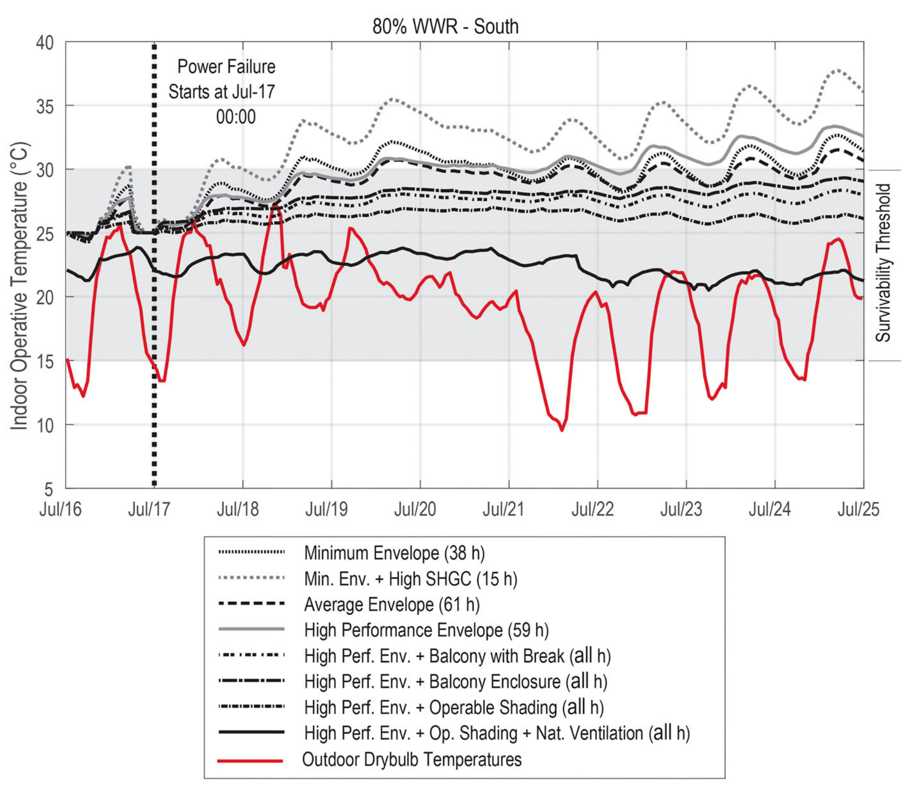

Figure 15. Passive survivability (PS) performance for a south-facing unit with an 80% window-to-wall ratio (WWR) under summer conditions.

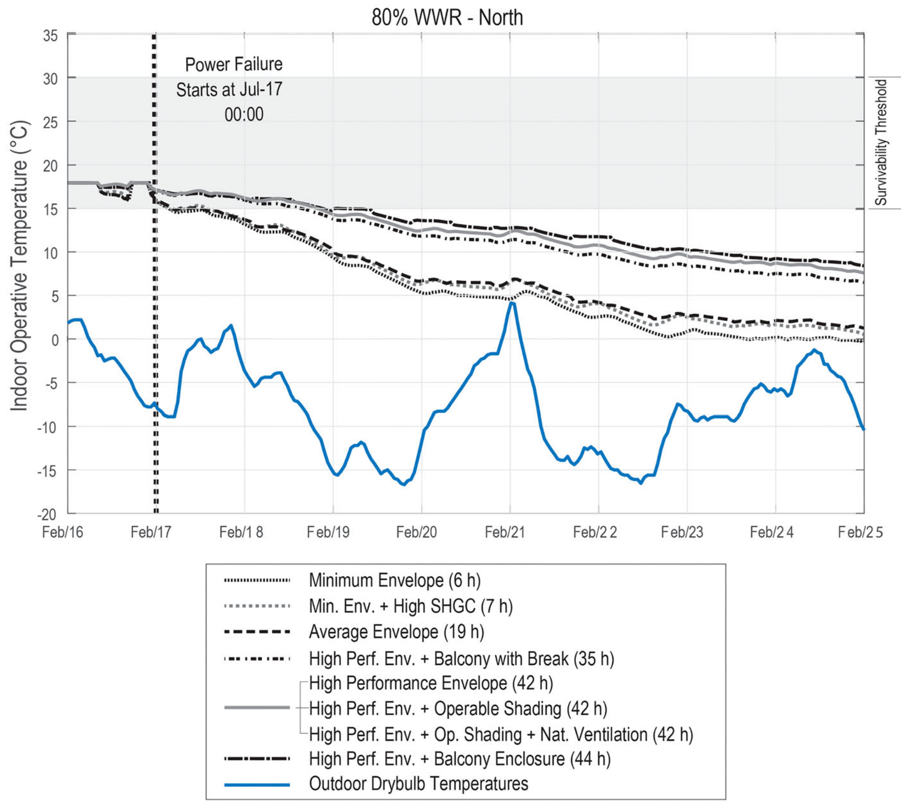

Figure 16. Passive survivability (PS) performance for a north-facing unit with an 80% window-to-wall ratio (WWR) under winter conditions.

useful for summertime power failures. Enhanced hot climate PS may also benefit from the deployment of passive cooling techniques presented in the literature (Santamouris, Pavlou, Synnefa, Niachou, & Kolokotsa, 2007).

Discussion

The research presented in this paper was motivated by two factors: the unacceptable levels of comfort and resilience exhibited in modern, highly glazed MURBs; and how the conventional deployment of building performance simulation has failed to improve these critical aspects of buildings substantially, in particular housing. Constructing detailed energy simulation models that include all passive and active features is time consuming and the volume and complexity of output data are difficult to interpret. By focusing exclusively on passive measures and assuming that buildings are in free-running mode, the modelling and visualization of TA and PS metrics may be both time and cost-efficient means of informing the early stages of design to enhance passive performance.

Public health organizations may also benefit from this research since it can be used to develop evidence to advocate for necessary changes to housing policies and building codes. There are certain types of buildings such as hospitals, hospices, community housing, shelters and child daycare centres that ought to exert a lower carbon footprint while affording an acceptable level of PS. Much work is needed to embody TA and PS thresholds as MR for public health and safety.

Research conducted for apartment building typologies indicates that TA and PS metrics are well correlated below certain thresholds of EUI, particularly where only annual space heating and cooling loads are considered, independent of lighting and plug loads. But the work presented herein only represents a promising method for exploring how these kinds of 'vital signs' for buildings can become rigorously tested and refined to serve as reliable indicators of *in situ* building performance.

A number of limitations in the research are openly acknowledged, and it is useful to review them. First, only one building typology (apartment buildings) and one construction typology (reinforced concrete) have been assessed. The modelling assumptions are generic in that typical values were assumed and there was only a cursory sensitivity analysis performed at the outset of the study as opposed to an extensive consideration of a broad range of parameter values. There is no evidence

Table 3. Passive survivability (PS) performance in Toronto, Vancouver and Adana associated with various passive measures corresponding to cases described in Tables 1 and 2.

			Base case 80% or 60% WWR minimum envelope	**Case 4 80% or 60% WWR; high-performance envelope**	**Case 9 80% or 60% WWR; high-performance envelope and operable shading and natural ventilation**	**Base case 40% or 30% WWR; minimum envelope**	**Case 4 40% or 30% WWR; high-performance envelope**	**Case 9 40% or 30% WWR; high-performance envelope and operable shading and natural ventilation**
Toronto	South Unit_2 × 1	PS – winter (hours)	118	All	221	124	All	All
		PS – summer (hours)	38	59	All	183	182	All
	North Unit_2 × 1	PS – winter (hours)	6	42	42	30	64	64
		PS – summer (hours)	65	187	All	469	423	All
Vancouver	South Unit_2 × 1	PS – winter (hours)	316	All	All	All	All	All
		PS – summer (hours)	135	134	All	183	182	All
	North Unit_2 × 1	PS – winter (hours)	49	164	164	99	370	370
		PS – summer (hours)	All	328	All	All	All	All
Adana	South Unit_2 × 1	PS – winter (hours)	All	All	All	All	All	All
		PS – summer (hours)	37	59	424	40	86	All
	North Unit_2 × 1	PS – winter (hours)	All	All	All	All	All	All
		PS – summer (hours)	38	60	All	65	103	All

Notes: PS is indicated as consecutive hours before habitability thresholds are exceeded.
80% and 40% window-to-wall ratios (WWRs) are highest and lowest ranges respectively for Toronto and Vancouver.
60% and 30% WWRs are highest and lowest ranges respectively for Adana.

to suggest the results are applicable beyond the types of MURBs that are commonly constructed.

A second major limitation involves the reliance on operative temperatures to predict acceptable comfort levels acknowledging that the literature indicates the criticality of extreme factors that remain difficult to incorporate into conventional simulation tools. The modelling of TA does not take into account weather variability due to climate change, and the approach to occupant comfort is simplistic and should consider incorporating a probabilistic adaptive thermal comfort (Coley, Herrera, Fosas, Liu, & Vellei, 2017). Further, no consideration was given to the impact of these passive measures on indoor environmental quality, which is a known concern in low-energy housing (Phillips & Levin, 2015).

Third, measures of PS assume ideal and consistent occupant behaviour to optimize the performance of passive measures that may be controlled, such as shading devices, operable windows and clothing levels. It is not clear if typical building occupants have the knowledge to operate their buildings optimally during extreme events by purely passive means. Moreover, occupants' ability to improve their comfort actively is dependent on their physical ability, which may be limited for the most vulnerable (*e.g.* the elderly).

Finally, complex phenomena such as air leakage and stack effect in real buildings contradict the assumption that individual suites are compartmentalized and isolated from one another aerodynamically, especially in tall buildings. While the conductive heat transfer among adjacent suites is negligible based on their relatively small potential temperature differences, field studies of air movement in buildings during prolonged power outages coinciding with extended periods of extreme weather have not been conducted, judging from the most recent literature review. There is still no reliable and statistically significant means of confirming if air movement is different between a building that is entirely passive versus the same building with active systems for moving heat and air. The underlying physics is constant, but the comparative behaviours remain unknown.

The work conducted and results to date confirm that further research is needed to establish key performance indicators (vital signs) that are simple, accurate, economical and accessible to architects at the early stages of design.

Conclusions

This paper has investigated how the visualization of time-based metrics can be used effectively to inform the early stages of design so that enhanced energy performance, comfort and thermal resilience may be achieved in buildings. Work conducted to date is promising and holds the potential to provide a common language and close the communication gap between architects and engineers through such visualization techniques.

Ideally, building design teams would be able to obtain critical metrics (vital signs) such as TA and PS using relatively simple, fast, accurate and intuitive simulation tools. These vital signs would be reliably correlated to levels of desired and/or legislated levels of energy efficiency, comfort and resilience in actual buildings. As design work proceeds, more sophisticated simulation tools could be applied to refine the energy design and integrate control strategies while being confident early-stage design decisions will not contribute to an unacceptable performance gap. There remains a great deal of research needed to accomplish this ideal for reliable building design.

Stemming from the larger body of work conducted within this study, several important issues have emerged that require further research – the first three presented are related to new areas identified during the study that need further attention, while the last three point to existing and ongoing research gaps:

- A common set of conventions, protocols and benchmarks are needed to render TA and PS metrics more useful and consistent across a range of building typologies.
- The comfort and survivability indoor temperature thresholds vary considerably in the literature. It is critical to define both comfort thresholds that are appropriate for the analysis of passive measures in naturally ventilated buildings and survivability thresholds under extreme conditions of high temperatures and humidity. There is a need for a standard that can guide proper simulation methods and assumptions to provide consistent and reliable metrics.
- The correlation between individual suite behaviour and whole-building performance remains to be thoroughly investigated. If the 'weakest links in the chain' are provided with measures to meet acceptable levels of comfort and resilience aspirations, what is the resulting behaviour when they are applied across the fabric of the entire building?
- A consistent method for compiling a set of weather data that reflect the impacts of climate change on extreme weather events must be developed and commonly accepted. Typical useful service lives of buildings are such that forecast changes in climate and extreme weather phenomena are reasonably certain and must therefore be considered.

- Models for thermal comfort in naturally ventilated buildings where inhabitants can actively modify clothing and activity levels are still under development, and the currently available models have major limitations.
- The accurate modelling of natural ventilation is critical for hot weather TA analysis and the validation of current models available in the various building energy-simulation software packages is warranted.

Despite these issues and the aforementioned limitations, the research presented in this paper demonstrates that the assessment of passive strategies, by visualizing TA and PS metrics, is a promising means of guiding the early stages of design for low-energy buildings.

Acknowledgments

The authors would like to thank Mr. Mostapha Sadeghipour, developer of Ladybug and Honeybee, who assisted in the coding of the custom design for the TA graphs.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The authors gratefully acknowledge the financial support of the Ontario Ministry of Research and Innovation and the BC Housing Building Excellence Research and Education Grants Program.

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