AN OVERVIEW: THERMAL RESILIENCE OF BUILDINGS AND RELATED METRICS

Thermal Energy Systems Resilience in Cold/Arctic Climates Consultation Forum
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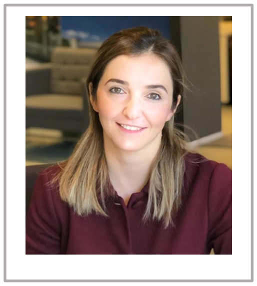
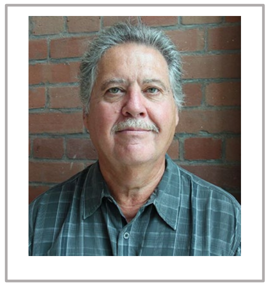
  

The world is entering an age of climate change where people are witnessing an increased frequency and severity of extreme weather events. While these extreme events are seldom unmitigated disasters, they have the potential to disrupt our daily lives, business operations, and possibly jeopardize private and public property, and human safety.

What is Thermal Resilience?

Resilience is the capability to adjust to changing circumstances and to maintain functionality and strength in the face of stress or disruption (Kesik 2015). When disasters occur, it is vital that buildings continue to provide shelter under extreme weather conditions so that inhabitants can safely and comfortably survive until normal operating conditions are restored. In that sense, thermal resilience is mainly 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.

The resilience of buildings is largely determined by the performance of the envelope. Robust envelope design ensures that buildings are durable, energy efficient, and comfortable, and also that they provide shelter under extreme conditions. It is hypothesized that an apartment suite that is robust with regards to performance during regular operation shall also be resilient (O'Brien and Bennet 2016).

Resilience vs. Sustainability

As the ever-growing interests in sustainability and resiliency increase, there have been conflicting opinions related to the uses of the terms. It is important to recognize that sustainability is about reducing the use of resources where as resiliency is about increasing survival. Sustainability is mostly about lowering our buildings' impact on climate change, where as resilience is about our buildings' action during the extreme weather events due to climate change. There are studies claiming that if a building is resilient, it is already sustainable while the reverse may not always be the case.

In the context of a low carbon economy, we may assume that low energy buildings will become normative within codes and standards. While cost effectiveness cannot be ignored, factors such as carbon pricing may be expected to reward energy efficiency and carbon reductions to a point where technical feasibility will establish minimum performance requirements. Specifically, minimum requirements for the thermal efficiency of building enclosures may be expected to approach levels consistent with what is presently found in leading edge low energy buildings. But designers should be mindful that liveability, not just efficiency, is also an integral aspect of the sustainability agenda.

Tornadoes, hurricanes, record rainfalls, ice storms, droughts, and heat and cold waves are among the extreme weather events that will challenge the resilience of building enclosures. High performance envelopes can keep the heat both in and out, and this makes it possible for inhabitants to remain in their dwellings for extended periods during power outages when heating or cooling equipment is disabled. Because indoor temperatures change more slowly, they increase a building's "passive survivability" (Schoeman 2015).

Though building codes have requirements for thermal comfort, they do not have requirements for indoor resilience or the ability for a building to maintain safe indoor conditions during long periods without power for mechanical systems (Holmes et al. 2015). Some cities, such as New York City, are developing building standards that require buildings to provide survivable conditions during power outages (Building Resiliency Task Force 2013). For reasons of health, safety, and resilience, the time-based metrics of thermal autonomy and passive habitability are expected to find their way into codes and standards one day (Wilson 2006), but in the meantime they represent better practices that add value, safety, and security.

What are the Common Metrics?

Thermal autonomy and passive habitability are two related and critical metrics for the thermal resilience of buildings.

Thermal Autonomy (TA) is the fraction of time that a building maintains comfortable indoor conditions without inputs from active systems. The metric for thermal autonomy is based on comfort conditions defined as a range of operative indoor temperatures between 18 °C and 25 °C (64 °F and 77 °F).

To assess thermal autonomy, a building is put into "free-running" mode where all of the active system and occupancy inputs are turned off in an energy model and the thermal performance of the building is simulated for a typical weather year. The number of hours where the indoor temperature is between 18 °C and 25 °C is compared to the entire year which comprises 365 days X 24 hours per day = 8,760 hours. For example, if a free-running simulation indicates that the building is between 18 °C and 25 °C for 4,500 hours, then the thermal autonomy is expressed as a passive fraction of 4,500/8,760 = 51.4%.

The higher the thermal autonomy, the more the passive enclosure system contributes to managing acceptable indoor conditions, and the less it relies on active system inputs to achieve thermal comfort. Recent research indicates the greater the thermal autonomy, the smaller the peak and annual energy demands for active space heating and cooling.

It is often debated as to whether or not the tabulation of numerical data is a form of visualization, but it is generally accepted that some types of numerical data are needed to inform the thermal resilience design process. Tabulated data are necessary but insufficient to inform early stages of design. Unlike code compliance, thermal resilience involves time-based metrics which are best conveyed graphically.

A very useful visualization technique for assessing thermal resilience involves the use of a carpet plot that indicates the "too hot," "acceptable," and "too cold" hours in each day over a typical weather year **(Figure 1)**. When a progression of passive measure combinations is plotted, it is relatively easy to identify the trends as well as the particular contributions of various passive measures to cold weather and hot weather thermal autonomy.

Two important relationships emerge from this visualization. First, the percentage of time when it is too cold does not appreciably change regardless of the enclosure thermal efficiency. This may be due to the excessive 80% window-to-wall ratio. Second, the relationship between the high-performance envelope, operable shading, and natural ventilation is synergetic with each measure significantly improving performance from 43% too hot down to practically 0% too hot. Something that is not indicated in this carpet plot is just how hot and cold it is inside the building on a daily, seasonal, and annual basis.

On the other hand, a plot of hourly free-run temperatures over a typical weather year provides critical information about the frequency and intensity of critical events, such as freezing **(Figure 2)**. Unlike the carpet plot reflecting periods of acceptable and unacceptable thermal comfort, the hourly plot of free-run temperatures indicates fluctuations and extreme temperatures. The degree of thermal autonomy is not as conveniently summarized in numerical format, but the thermal response of the building can be more fully appreciated and explored.

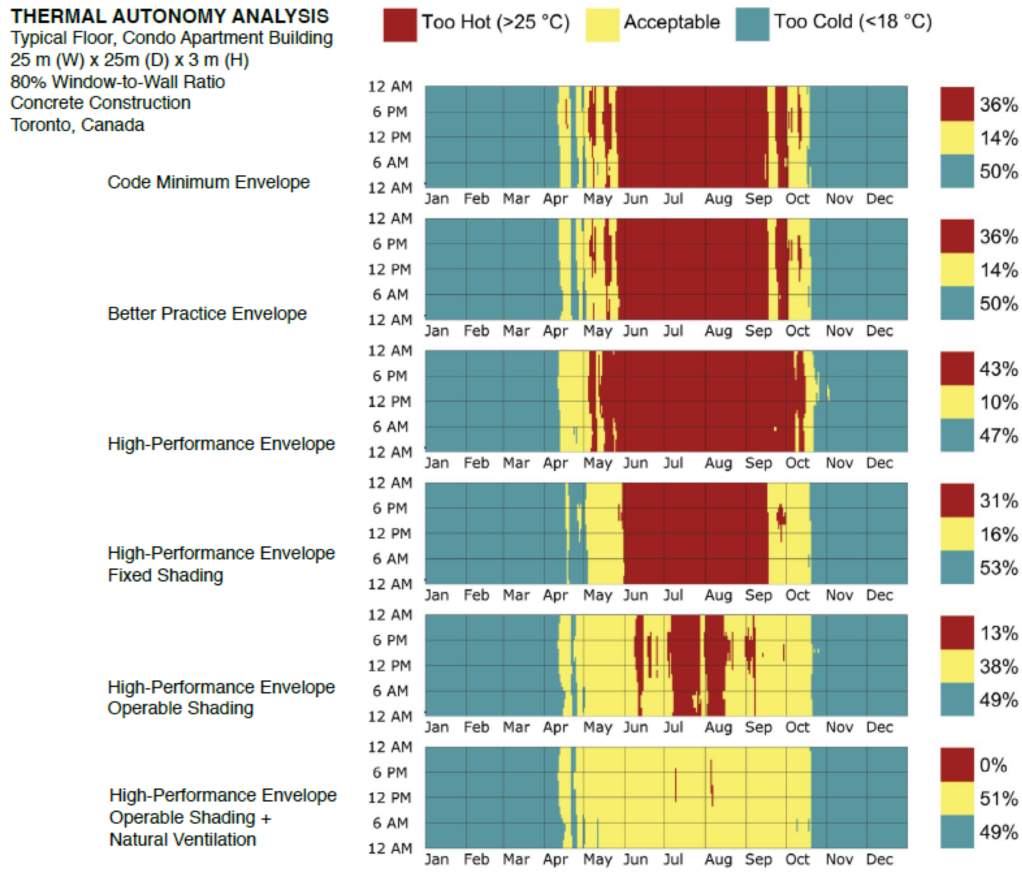


Figure 1. Comparison of TA simulation results for various passive design strategies

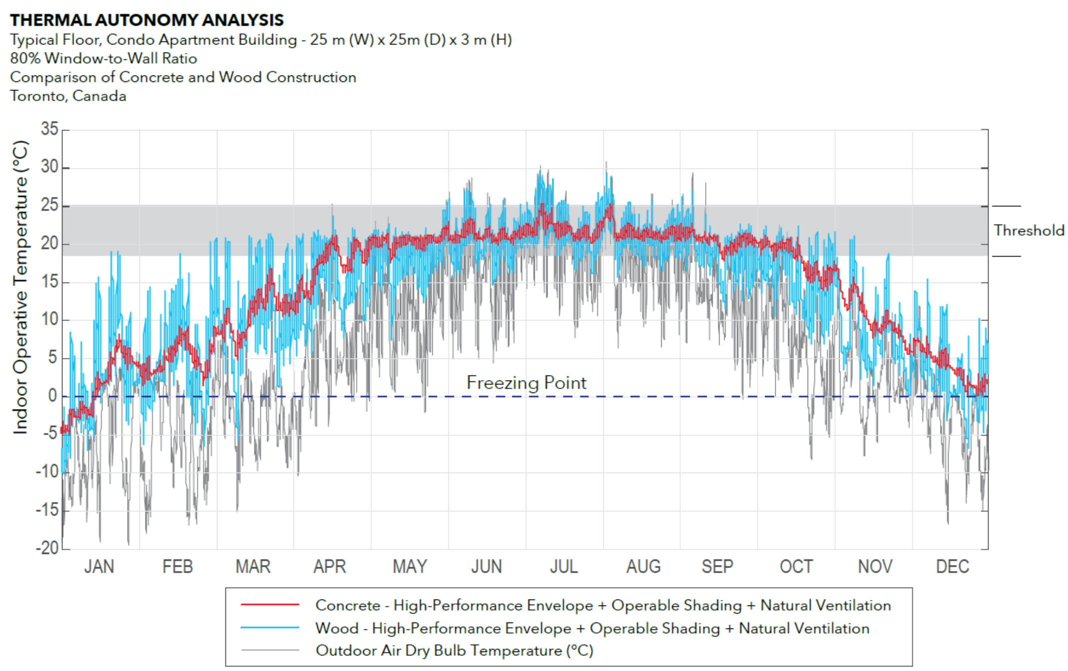


Figure 2. A plot of hourly free-run temperatures over a typical weather year

Overall, the contributions that thermal autonomy makes to thermal resilience are manifold. First, the useful life of active system equipment (HVAC) is extended to provide service over a longer period of time, thus enhancing its reliability and durability. Second, energy sources supplying the active systems are conserved and, for remote facilities that store energy on site (wood, propane, oil, etc.), this provides better energy security during periods of inclement weather when delivery of energy may be impaired. Third, the peak demands on the energy grid are reduced resulting in fewer brownouts while extending the useful capacity of the grid. Fourth, the carbon footprint of the building may be significantly reduced to positively contribute to climate change mitigation and reduce even more frequent and severe extreme weather events in the future.

Passive Habitability (PH) is a measure of how long a building remains habitable during extended power outages that coincide with extreme weather events. Unlike thermal autonomy, where thermal comfort criteria are applied to obtain a performance metric, habitability criteria are related to marginally acceptable, or reasonably tolerable, temperatures.

Guidelines for passive survivability indoor temperature and humidity conditions remain to be fully developed and standardized. To simplify energy modeling of passive habitability, the lower indoor operative temperature threshold of 15 °C (59 °F) is often used for the space heating period. For the space cooling period, an operative temperature of 30 °C (86 °F) is normally used for the upper threshold. At this time, defining suitable and practically enforceable indoor heat thresholds remains problematic for a number of reasons, including the age and health of inhabitants, the achievable rate of natural ventilation, and the provision of overheating management measures, such as shading devices, that are available for manual deployment by the inhabitants.

Passive habitability analysis can provide greater resolution for comparative assessments of passive measure strategies.

Cold weather passive habitability is very challenging in cold climates depending on the solar orientation of a suite or zone. It also is affected by whether or not the suite or zone is effectively compartmentalized, or if airflows and heat energy transfer across adjacent spaces. **Figure 3** represents cold weather passive habitability (PH) for a north-facing suite in a condominium building with floor-to-ceiling window-wall façade, which is the most critical unit in the entire building. In a matter of a few hours, the conventional code minimum building envelope only provides 6 hours of habitable shelter. The high-performance enclosure provides almost two days (44 hours). The very same set of passive measure combinations yield dramatically different cold weather habitability results. This can be expected for north-facing suites/zones in most of Climate Zone 6 where an absence of solar gains is evident in a constantly declining indoor temperature profile.

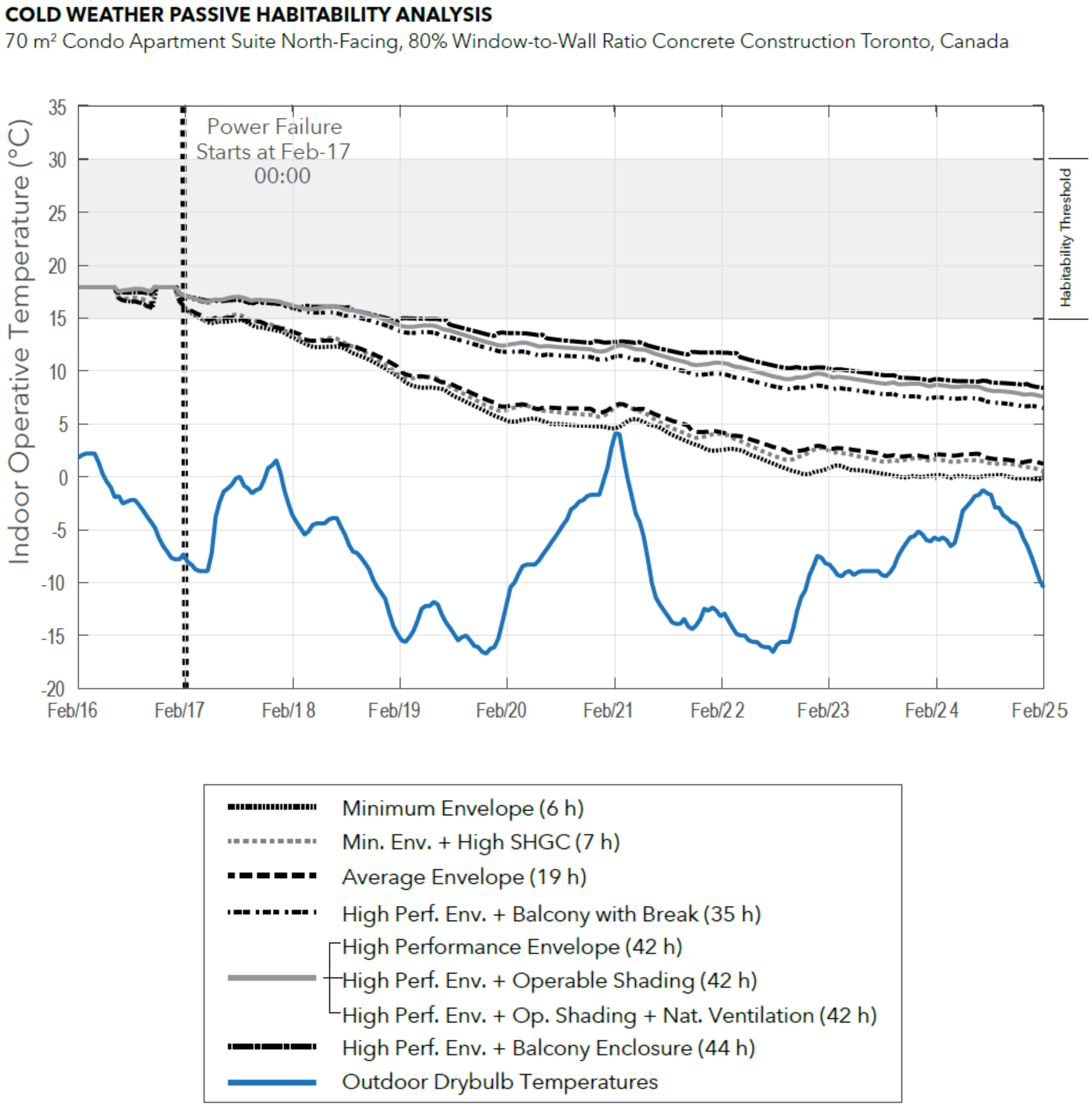


Figure 3. Figure 4. Comparison of Passive Habitability results in cold weather.

Detailed information, case studies and guidance on building energy modeling protocols for determining thermal autonomy and passive habitability are provided in the "*Thermal Resilience Guide v1.0*" (https://www.daniels.utoronto.ca/faculty/kesik_t/PBS/Kesik-Resources/Thermal-Resilience-Guide-v1.0-May2019.pdf), which was developed by the authors in May 2019.

What are the Main Strategies to Enhance the Resilience of Buildings?

Many strategies are available to enhance the resilience of buildings. Most of them are simple and relatively inexpensive. The most persistent attributes are the passive features such as the building form and solar orientation, the overall effective U-value of the enclosure, fenestration, and fixed shading devices, and the building's thermal mass and airtightness.

Passive systems largely regulate the capacities and types of technologies used for environmental conditioning, and this has implications for architectural and active systems design. Passive systems are also the only strategies that can address issues of thermal comfort and resilience, since active systems are inoperable when they are no longer energized, as occurs when extreme weather events knock out the electricity supply grid. For these reasons, passive systems should be privileged in the design of buildings and resolved before introducing active systems. Also, it is often overlooked that active systems cannot conserve energy, only more or less efficiently convert energy to serve a purpose. Hence, it is critical to begin building performance modeling with robust default values for passive measures at the early stages of design (Hiyama 2015).

This paper briefly discusses the passive design strategies related to building envelope by considering relevant literature. Note that some of the strategies yield benefits by achieving some energy requirements while having a negative impact on others. Therefore, it is important to assess the performance of whole building (Radhi 2008).

The influence of overall effective U-values, as well as window-to-wall ratios and window apertures (window to floor area ratio) are very significant (Morrison Hershfield 2011). A study by Cheung et al. (2005) proves that both annual and peak cooling loads are reduced more with increased thickness of insulation at any position. However, once a critical level of insulation has been reached, heating demand is reduced at a lower rate with thicker insulation (Pacheco 2012). This situation is called the "rule of diminishing returns" in a study by Lechner (2001).

For reinforced concrete structures, the influence of thermal bridging at balconies is significant, and becomes relatively more critical as the overall effective U-value of the exterior enclosure is reduced. The provision of thermal breaks in cantilevered, reinforced concrete balconies represents a critical passive measure, all comfort benefits aside (Ozkan et al. 2017)

Balconies in new buildings are very common even though their use and appeal may diminish with increasing building height (Everett 2013). Since these serve as fixed shading devices, they may compromise passive solar gains needed for thermal autonomy, even though they improve energy efficiency overall if they incorporate thermal breaks to maintain the thermal efficiency of the enclosure. It is beneficial to assess balcony shading versus adjustable shading devices to determine if the latter can achieve both the passive solar gain and shading benefits based on location.

Another important set of parameters is moveable insulation panels (MIPs), that inhabitants can deploy to manage solar gains, daylighting, and heat transfer. A study of MIPs indicates significant potential for the application of this technology to energy conservation and enhanced daylighting (Du Montier et al. 2013). It is conceivable that many of the conflicts between passive heating and cooling arising from cantilevered balconies above windows could be avoided through an appropriate application of MIPs. It is also possible that various retractable balcony enclosures could dampen and minimize negative side effects of fixed shading devices such as balconies.

Shutters represent armouring, an ancient resilience strategy that has made a recent come back due to climate change. In addition to offering protection from wind-borne projectiles that can damage windows and break glass, insulated shutters can increase the thermal comfort levels and even enhance daylighting. Furthermore, building envelopes can comprise multiple layers of defence against heat, air, and moisture movement. Effective daylighting and natural ventilation can supplant artificial lighting and mechanical ventilation when the grid goes down (Kesik and O'Brien 2017). In a study by Holmes, a generic residential building and various envelope design techniques were evaluated with regard to their ability to passively maintain indoor temperatures during a prolonged electrical blackout in order to recommend a combination of design techniques for optimal residential passive habitability design in the US northeast (Holmes 2015). The author concluded that a combination of low window-to-wall ratios, external operable shading, and an increase to code minima for insulation and natural ventilation would likely provide better habitable conditions during winter and summer blackouts.

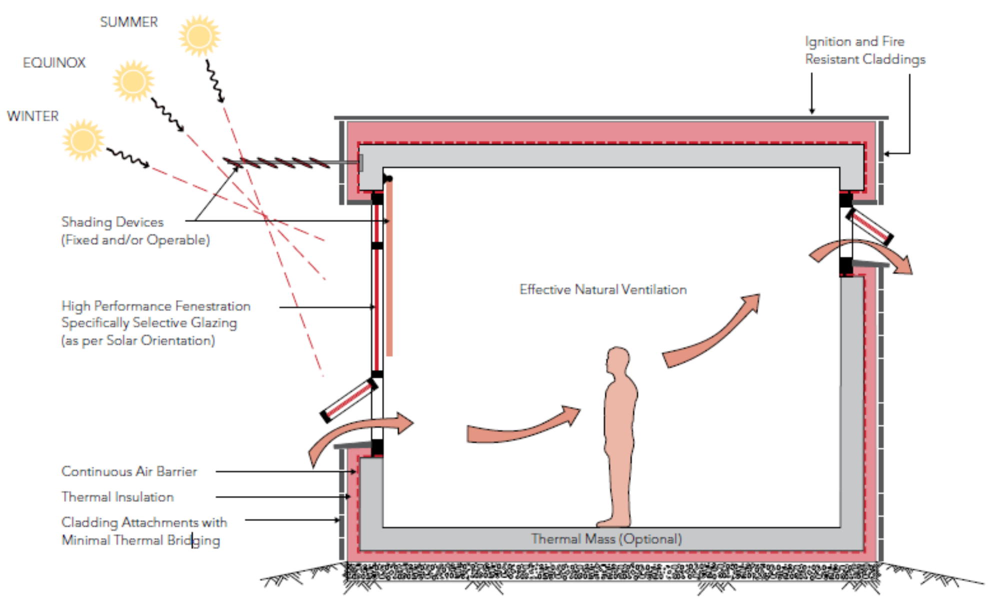
In another study, Santamouris et al. presented passive cooling techniques. In summary, the authors identify passive cooling techniques as: thermal improvement by the use of outdoor and semi-outdoor spaces, layout and external finishing, solar control and shading of building surfaces, thermal insulation, control of internal gains, control of the thermal storage capacity of the building structure, and the potential for disposal of excess heat of the building (Santamouris et al. 2007). Also, the research suggests that high reflective coatings are affordable and easily accessible options for buildings, which can considerably reduce outdoor and indoor temperatures and enhance comfort in the warmest climates. Furthermore, the authors suggest that ground cooling, ventilation technologies, and the design and positioning of openings are important considerations to improve indoor comfort, enhance indoor air speed, and decrease indoor pollutant concentration.

Manually and/or automatically invoked measures for shading and augmenting the thermal efficiency of both opaque and transparent enclosure assemblies hold the potential to provide inhabitants with more adaptive, efficient, comfortable, and resilient dwellings. This holds opportunities and challenges for architectural design in going from static to dynamic facades. It is important to appreciate that these new approaches must incorporate serious consideration of the influence of building occupant behavior on their effectiveness (Brown 2015).

Once robust passive measures for the enclosure are achieved, airtightness is essential to preserve the performance gains afforded by the thermal enclosure. Airtightness requirements appear in building codes and standards, but they may not always be enforced, such that significant variations of air leakage rates have been reported by field testing (RDH Building Engineering 2013). The control of outdoor air leakage is also critical to the proper operation of ventilation systems (Ricketts and Straube 2014). Even though ventilation and free cooling are associated with active systems, they enhance energy efficiency and a failure to control air leakage will compromise HVAC system performance.

Thermal autonomy in multi-unit residential buildings for the Toronto climate zone has been studied recently, and the results indicated that thermal autonomy was very poor without occupant interaction; the results suggest that adaptive opportunities are at least as important as building envelope design with regards to maintaining comfort in the event of power or system failure (O'Brien and Bennet 2016).

In summary, the most effective passive strategies to increase thermal autonomy and passive habitability for skin-load dominated buildings are: overall effective U-value of the enclosure (with minimization/elimination of thermal bridging); window to wall ratio; window U-value and solar heat gain coefficient; window aperture (window to floor area ratio); airtightness; shading; and solar orientation.



Thermal resilience involves the application of basic building science.
Passive measures for buildings have the advantage of requiring no external energy sources to deliver habitable shelter under a variety of extreme conditions.

Discussion

Several studies conducted so far indicate that thermal autonomy and passive survivability metrics are well correlated below certain thresholds of energy use intensity, particularly where only annual space heating and cooling loads are considered, independent of lighting and plug loads. And the approach presented herein represents a promising methodology for exploring how the relevant passive strategies can become rigorously tested and refined to achieve environmentally responsible, resilient building design.

It is well-known that architects' early design decisions impose a major impact on a building's energy performance. With the approach discussed in this paper, architects and designers will be able to use simulation tools in a very simple, fast, and reliable way by interpreting the simulation results intuitively through time-based metrics of thermal autonomy and passive survivability.

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 modeling and visualization of thermal autonomy and passive survivability 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 daycares that ought to exert a lower carbon footprint while affording an acceptable level of passive survivability. Much work is needed to embody thermal autonomy and passive survivability thresholds as minimum requirements for public health and safety. But in the short run, they may provide guidance to help architects consider and better understand the relationships between passive parameters such as such as form, size, orientation, fenestration, materials, shading, climate factors, gains, conduction, and infiltration.

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