

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**A NEW APPROACH TO GUIDE EARLY STAGES OF BUILDING DESIGN
TO IMPROVE PASSIVE PERFORMANCE THROUGH THE TIME-BASED
THERMAL RESILIENCE METRICS**



Ph.D. THESIS

Aylin ÖZKAN

Department of Architecture

Building Science Programme

OCTOBER 2018

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**BİNALARIN ERKEN TASARIM AŞAMASINDA PASİF PERFORMANSINI
ZAMANA DAYALI TERMAL DİRENÇ ÖLÇEVLERİNE GÖRE ARTIRMAK
İÇİN YENİ BİR YAKLAŞIM**

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To my precious spouse and children,

FOREWORD

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Aylin OZKAN



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ABBREVIATIONS

App	: Appendix
ITU	: Istanbul Technical University
PS	: Passive Survivability
STIMAPs	: Spatio-Temporal Irradiation Maps
TA	: Thermal Autonomy
UPenn	: University of Pennsylvania
zEPI	: Zero Energy Performance Index





SYMBOLS

$^{\circ}\text{C}$	: Celcius
$^{\circ}\text{F}$	: Fahrenheit
$T_{op}(t)$	: Indoor Operative Temperature at t^{th} hour of the 8760-hour year
T_{max}	: Maximum Comfort Threshold for TA
T_{min}	: Lower Comfort Threshold for TA





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A NEW APPROACH TO GUIDE EARLY STAGES OF BUILDING DESIGN TO IMPROVE PASSIVE PERFORMANCE THROUGH THE TIME-BASED THERMAL RESILIENCE METRICS

SUMMARY

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, in particular housing, can withstand prolonged power outages during extended periods of extreme cold and hot weather to passively provide habitable shelter.

The aim of this thesis is to develop a new approach to improve passive performance of buildings through the time-based building thermal resilience metrics of thermal autonomy (TA) and passive survivability (PS, also termed thermal resilience). In this study, thermal autonomy is a measure of the percentage of time a building can deliver comfort passively, without any additional active systems; and passive survivability is a measure of the length of time a building provides habitable conditions during an extended power outage as a result of extreme weather. Simulations of typical apartment suites are conducted in three given climatic locations: Toronto, Canada, warm humid summers, cold winters, and moderately sunny; Vancouver, Canada, overall cool and humid; Adana, Turkey, humid and dry summers, warm and rainy winters. Based on the simulation results, this study intends to show the relationship between these time-based building resilience metrics and conventional energy performance metrics, particularly energy use intensity. The main objective is to fill the communication gap between engineers and architects by providing a common language through a practical visualization technique. As a result, architects may have better control over their design considerations and improve environmental building performance at the same time.

The idea is tested through a survey study which assessed the effectiveness of proposed approach through the visualizations of thermal autonomy and passive survivability analysis. The survey results revealed that engineers use current energy related metrics more than architects in the discussion of building performance. Compared to energy units, such as Watts and kilowatt-hours, performance metrics based on a measure of "time" are more intuitive, and correlate well with conventional energy performance metrics.

Keywords: time-based metrics; passive performance; thermal resilience; energy simulations; visualization.



BİNALARIN ERKEN TASARIM AŞAMASINDA PASİF PERFORMANSINI ZAMANA DAYALI TERMAL DİRENÇ ÖLÇEVLERİNE GÖRE ARTIRMAK İÇİN YENİ BİR YAKLAŞIM

ÖZET

Günümüzde artmakta olan küresel iklim değişikliği sonucu bina kodları ve standartları, bina enerji verimliliğinin artırılması ve karbon ayak izlerinin azaltılmasını destekleyici yönde değişikliklere gitmektedir. Ayrıca, binaların, özellikle konutların, aşırı soğuk ve sıcak havalarda uzun süreli elektrik kesintilerine dayanabilmelerini sağlamak, pasif olarak yaşanabilir ortamlar tasarlamak mimaride önem kazanmıştır.

Bu tezde, zamana dayalı termal direnç ölçevleri olan “thermal autonomy (TA)” ve “passive survivability (PS)” kullanılarak binaların pasif performanslarını artırmaya yönelik yeni bir yaklaşım sunulmuştur. Çalışmada, TA herhangi bir ek aktif sistem olmaksızın, bir binanın pasif bir şekilde belirli konfor koşullarını sağlayabileceği sürenin yüzdelik ölçüsüdür. PS ise, bir binanın sıradışı hava koşulları nedeniyle uzun süreli bir elektrik kesintisi gerçekleşmesi durumunda, yaşanabilir ortam koşullarının sağlanabildiği sürenin ölçüsüdür. Önerilen yaklaşım doğrultusunda simülasyonlarda tipik apartman modülleri 3 farklı iklimde değerlendirilmiştir: Toronto, Kanada, sıcak nemli yazların, soğuk kışların görüldüğü ılımlı güneşli bir iklim; Vancouver, Kanada, genel olarak serin ve nemli; Adana, Türkiye ise sıcak ve kurak yazların, ılık ve yağışlı kışların hakim olduğu iklim türüdür. Simülasyon sonuçlarına göre bu çalışma, zamana dayalı bina direnç ölçevleri ile konvansiyonel enerji performans ölçevleri arasındaki ilişkiyi göstermeyi amaçlamaktadır. Temel hedef, pratik bir görselleştirme tekniği ile mühendisler ve mimarlar arasında ortak bir dil sağlayarak iletişim boşluğunu doldurmaktır. Sonuç olarak, mimarların tasarımıyla ilgili düşüncelerini entegre tasarım aşamasında daha iyi kontrol edebilecekleri ve aynı zamanda çevresel bina performansını geliştirebilecekleri düşünülmektedir.

Günümüzde, bina performans simülasyon araçlarının tasarım kararlarını yönlendirmek için mimarlar tarafından erken tasarım aşamalarında nadiren kullanıldığı kabul edilmektedir (Hemsath, 2013). Bununla birlikte, tasarımın erken aşamalarında alınan kararlar en büyük enerji ve maliyet tasarrufu sağlanmakta iken (Hensen, 2011), günümüzde yaygın olan bina tasarım uygulamaları enerji azaltma stratejilerini tasarım sürecinin ancak sonunda göz önünde bulundurmaktadır (Samuelson ve ark., 2012). Bu aşamada gerçekleştirilen değişikliklerin pahalı ve yıkıcı sonuçları olabileceği göz önünde bulundurulmalıdır (Attia ve ark., 2012). Bu tezin temel odak noktası, mimarların yüksek performanslı binalar elde etmek için tasarımın mümkün olan en erken aşamalarında entegre tasarım sürecine planlı ve hazırlıklı bir şekilde katılmaları gerektiğidir. Bu odak noktası da, mimari tasarım sürecinde enerji simülasyonunu yüksek performanslı binaların erken tasarım aşamasına entegre eden pratik yaklaşımlara ve grafiksel geri bildirim yöntemlerine olan ihtiyacı gündeme getirmektedir. Ayrıca, mevcut bina performans simülasyon

yöntemleri, belirli hedefler için uygun performans ölçevlerine ve göstergelerine gerek duymaktadır (Samuelson ve ark. 2016).

Mevcut simülasyon yaklaşımlarının çoğu kapsamlı girdi verileri gerektirmektedir (Ochoa ve Capeluto, 2009) ve bina performans simülasyonundan büyük miktarlarda çıktı sağlamaktadırlar (Attia ve ark. 2013). Tasarım ekipleri için, analiz çıktılarından en baştan ne çıkarılacağını bilmek çok daha iyi bir tasarım elde etmek için oldukça önemlidir ve zaman açısından çok verim sağlayacaktır (Ulukavak ve ark. 2006). Bu şu anda çoğu mimar tarafından bilinmemektedir.

Literatürde, erken tasarım aşamasında bina simülasyon araçlarının kullanılması ile ilgili konuları ortaya koyan birçok çalışma olduğu halde, erken tasarım sürecini daha iyi bilgilendirmek için zamana dayalı metrikleri kullanarak binaların ısı performansını görselleştirmeye yönelik oldukça az çalışma vardır.

Belirtilen bu sebepler ışığında bu tez, pratik bir simülasyon yaklaşımı ve görselleştirme tekniklerinin geliştirilmesine odaklanmıştır. Bu yaklaşımın kullanılmasıyla bina simülasyon araçları, erken tasarım aşamalarında pasif sistem entegrasyonu ve optimizasyonu için daha basit değerlendirmeler sağlayabilecektir.

Tezde esas olarak, “Thermal Autonomy” ve “Passive Survivability” değerlerini ölçmek için simülasyonların kullanılmasına yönelik bir yaklaşım sunulmuştur. Tipik apartman daireleri için on farklı tasarım örneği, önerilen yaklaşımı test etmek ve göstermek için üç farklı iklimde modellenmiş ve simüle edilmiştir. Sonrasında TA sonuçları, pratik grafiksel geri bildirim yöntemleri ile yaklaşımı açıklamak için analiz edilmiştir. Daha sonra, TA değerleri, bu zamana dayalı metriği doğrulamak için Enerji Kullanımı Yoğunluğu (Energy Use Intensity - EUI) sonuçlarıyla karşılaştırılmıştır. Son olarak, PS analizleri, TA ve PS arasındaki pozitif ilişkiyi göstermek için belirli sonuçlar incelenerek tartışılmıştır. Ayrıca, önerilen yaklaşımın etkinliği analizlerin görselleştirilmesini örnekleyen bir anket çalışması ile de test edilmiştir.

Genel olarak veriler, TA'nın, HVAC ve aydınlatma gibi aktif sistemler içeren daha karmaşık simülasyon modellerine ihtiyaç duymadan tasarımın erken aşamalarında alan ısıtma ve soğutma enerjisi taleplerinin yaklaşık bir göstergesi olarak kullanılabileceğini göstermektedir. Gelecekteki çalışmalarda, sadece apartman birimleri değil tüm bina için TA ile ısıtma ve soğutma enerjisi kullanım yoğunluğu arasındaki ilişki araştırılmalıdır. Bu yönlenmeye bağlı ısı kazançlarının ısıtma ve soğutma üzerindeki etkisini incelemek açısından daha yararlı olacaktır. Bu aşamada, “Thermal Autonomy” verilerinin, ısıtma ve soğutma enerjisi kullanım yoğunluğu ile güçlü bir şekilde ilişkili olduğu ve genel olarak, daha yüksek TA, daha düşük EUI olduğu sonucuna varılabilir.

Bunlara ek olarak, TA değerleri yüksek olan tasarımların, aynı zamanda daha iyi PS değerlerine sahip olma eğilimi gösterdiği görülmüştür. Literatürde PS iklim değişikliğinin sıradışı hava olaylarının ciddiyeti üzerindeki etkisini ve bu durumlardaki elektrik kesintisi sürelerini dikkate alan önemli bir metrik haline gelmektedir. Son zamanlarda iklim değişikliği, daha şiddetli rüzgârlar, daha yoğun yağışlar, ve hatta uzun süreli sıcak hava dalgalarının sonucu olarak kuraklık gibi daha sık ve daha şiddetli hava olaylarına neden olmaktadır. Bu nedenle günümüzde binalar, özellikle konutlar, iklim değişikliğinin etkilerine dayanmak için daha dirençli olabilecek ve bireylere uzun süreli elektrik kesintilerinde barınma imkanı sağlayabilecek şekilde tasarlanmak zorundadır.

Analizlerin görselleştirilmesi ile önerilen yaklaşımın etkinliğini test eden anket çalışmasının sonuçları özetle aşağıdaki gibi maddelendirilmiştir:

1. Anket sonuçları, mühendislerin mevcut enerji metriklerini bina performansının tartışılmasında mimarlardan daha fazla kullandığını ortaya koymuştur. Watt ve kilowatt-saat gibi enerji ölçütleriyle karşılaştırıldığında, “zaman” ölçüsüne dayanan performans ölçekleri daha sezgiseldir ve geleneksel enerji performans ölçekleriyle iyi bir korelasyona sahiptir.
2. TA grafiklerinin bir bina tasarımının mekanik sistemlerden bağımsız pasif olarak nasıl çalıştığını gösterdiği ve binanın enerji performansını anlamak için yeterli zamansal çözünürlüğe sahip olduğu düşünülmektedir.
3. Benzer şekilde, PS grafiklerinin bina seviyesinde pasif tasarım stratejilerini görselleştirmede etkili olduğu ve uzun süreli elektrik kesintisi sırasında iç ortam konfor koşullarını anlamak için yeterli zamansal çözünürlüğe sahip olduğu düşünülmektedir.
4. PS grafikleri ayrıca, insan ölçeğinde alışılmış metrikler (zaman ve sıcaklık) kullandığı için sıradışı hava koşullarına dayanıklı tasarım kararlarının iyileştirilmesi için de yararlıdır.
5. Edinilen önemli gözlemlerden biri de, katılımcılardan gelen, erken tasarım aşamasında, bina performans simülasyonunun bu görselleştirme tekniklerine ve ilgili metriklere odaklanarak, bunların enerji kullanımı yoğunluğu gibi geleneksel metriklerle ilişkilendirilmesi ve kod hedeflerine uyumun geliştirilmesi önerisidir.

Sonuç olarak, tasarımın erken aşamalarında TA ve PS metriklerinin kullanımı, aktif sistem ilavesi olmaksızın binaların serbest çalışma modunda basitleştirilmiş enerji simülasyonlarının yürütülmesini içerir. Böylece pasif tasarım stratejileri gerek tekli gerekse kombinasyonları, etkinlik açısından hızlı bir şekilde değerlendirilebilir. Tasarımda bir araya getirilecek pasif sistemler kararlaştırıldıktan sonra, ilave aktif sistemlerin daha ayrıntılı enerji modellemesi yapılabilir. Pasif stratejiler ve zamana dayalı performans ölçütlerine odaklanarak, tasarım ekiplerinin bina performansı açısından daha iyi mimari çözümler sağlayabileceğine inanılmaktadır.

Bu çalışmada geliştirilen yaklaşımın sağlayacağı en önemli bilimsel katkı bina simülasyonunun erken aşamalarda bina tasarım sürecine entegrasyonunu çözmeye yöneliktir. Bu projeye, yüksek performanslı sürdürülebilir bina tasarımı üzerine çalışan akademisyenlerin, tasarımcıların ve uygulama yapan mimar ve mühendislerin ilgi duyması beklenmektedir. Ayrıca, politika geliştiren yönetici gruplara enerji verimli binalarda pasif sistem entegrasyonunun nasıl ele alınacağı ve politikalarda etkin enerji kullanımı ve konfor hedeflerinin nasıl tasarlanacağı hakkında rehberlik sağlayabilir. Aynı ölçüde kamuoyu da daha iyi bina tasarım politikalarının uygulanmasından büyük yarar sağlayacaktır.

Anahtar Kelimeler: zamana dayalı metrikler; pasif performans; termal direnç; enerji simülasyonları; görselleştirme.



1. INTRODUCTION

Increased energy consumption in the world has been an important issue in recent years. The report of International Energy Agency (IEA) declares that the buildings sector is consuming the highest amount of energy in the world as shown in Figure 1.1 below (International Energy Agency, 2013). Therefore, buildings sector constitutes the largest energy saving potential accordingly. Designing, developing and maintaining high performance buildings rank among society's most important and influential investments which increase demands for the design of net zero energy and carbon neutral green buildings.

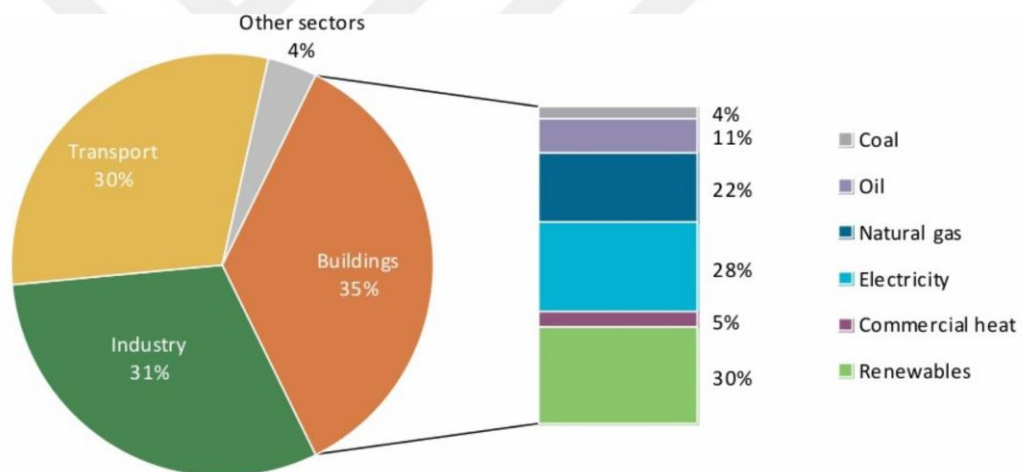


Figure 1.1 : Final energy consumption by sector and buildings energy mix, 2010 (International Energy Agency, 2013).

It is generally recognized that building performance simulation tools are used rarely at the early design stages by architects to inform their design decisions (Hemsath, 2013). Yet the largest savings of energy and cost are achieved with the decisions at the early stages of design (Hensen, 2011), common building design practices lean to consider energy reduction strategies at the end of the process (Samuelson et al. 2012), when changes can be expensive and disruptive to the design process (Attia et al. 2012). The main hypothesis of this thesis is that architects must deliberately engage the integrated design process at the earliest possible stages of design in order to achieve high performance buildings.

This hypothesis augments a need for practical approaches and graphical feedback methods that integrate energy simulation into the early design stage of high performance buildings within architectural practice. Building performance simulation methods require suitable performance metrics and indicators for particular objectives (Samuelson et al. 2016).

Furthermore, most of the current simulation approaches require extensive input data (Ochoa and Capeluto, 2009) and they provide large quantities of output from building performance simulation (Attia et al. 2013). For design teams, it is very efficient (time-wise) and helpful (for better design) to know what to extract from their analysis output at the very beginning (Ulukavak et al. 2006). This is currently unknown to most architects.

In view of this fact, and in acknowledgement of the supremacy of early decisions in the design of high performance buildings, this thesis is focused on the development of a practical simulation approach and visualization techniques. With the use of this approach building simulation tools could provide simpler evaluations for passive systems integration and optimization in early design phases.

This thesis mainly provides an approach for using simulations to quantify the thermal autonomy (TA) and passive survivability (PS) (the term “passive survivability” indicate “thermal resilience” here. In this study, thermal autonomy is a measure of the percentage of time a building can deliver comfort passively, without any additional active systems (Levitt et al., 2013); and passive survivability is a measure of the length of time a building provides habitable conditions during an extended power outage as a result of extreme weather (O’Brien and Bennet, 2016). It is different than non-thermal aspects of passive survivability, such as renewable energy generation or rainwater harvesting). Ten different passive design cases for typical apartment suites were modeled and simulated in three diverse climates to test and show the applicability of the proposed approach. Next thermal autonomy results are analyzed to illustrate the approach through practical graphical feedback methods. Then, the thermal autonomy numbers are compared to Energy Use Intensity (EUI) results to validate this time-based metric. Finally, passive survivability analysis are discussed through demonstrative results to show the positive relationship between thermal autonomy and passive survivability. Additionally, the authors conducted a survey study with architects and building simulation users to evaluate the influence

and popularity of these time-based metrics. The key survey findings are provided in the fifth chapter of this thesis.

1.1 Purpose of the Thesis

The most significant purpose of the thesis is the development of 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 and passive survivability. 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 better inform the early design process.

One of the main objective is to provide a common language and fill the communication gap between architects and engineers through a practical visualization technique, so that architects may maintain better control over their aesthetic and functional design values without compromising performance. In order for architects to achieve high performance buildings that minimize environmental impacts and lifecycle costs, they must meaningfully engage the integrated design process at the earliest possible stages of design.

Additionally, in this thesis it is hypotized that designs with high thermal autonomy also tend to have better passive survivability, which is becoming an important resilience metric in the literature that considers power blackout times and the impact of climate change on the severity and duration of extreme weather events. Recently, climate change is causing more frequent and severe weather events around the world, such as higher winds, periods of more intense precipitation (rainfall and snowfall), and increased incidences of freezing rain, as well as hotter and more extended heat waves accompanied by drought. Not only must housing be more resilient to withstand the effects of climate change, but it must also provide shelter when the energy grid goes down due to extreme weather events.

1.2 Significance of the Thesis

In the last decade, industry and government initiatives have hastened the design of energy efficient buildings through many rating systems, standards and codes. The European Parliament and the Council of the European Union (2010) oblige all new buildings in EU to be Net Zero Energy Buildings (NZEBS) by 2020. Furthermore, existing buildings are required to be converted to NZEBs through a cost effective retrofit procedure. The proposed practical approach in this thesis can provide valuable quantitative feedback to designers who are trying to meet the above standards in early design stage or energy efficient retrofit of building envelope.

In early design stages it is important to be able to evaluate multiple concepts and generate design alternatives. For the purposes of comparing the predicted performance of design alternatives in conceptual design, rather than when used to predict the performance of a single design solution, it is more practical to be relatively, rather than absolutely, accurate.

Findings of earlier efforts to integrate building simulation into the early stages of design process include:

- Unavailability or unreachability of appropriate computational tools or models.
- Complexity of input and outputs of simulation tools.
- Lack of usefulness and clarity of computational results in a design context.
- There are many different ways of interpreting the results. (They must be meaningful to persons who may not be specialists in energy simulation or similar analysis work (Radford, 1993). To benefit from building simulation tools high level of expertise is needed.
- Costs of building simulation efforts (both time and money-wise).

As a response to these issues, there is a high tendency of developing programs or tools specific to early design stages. As the main disadvantage of this effort, the users are still restricted to the features in a particular program or modeling environment, that is developed by a small group of researchers. (Hensen, 2004)

Some other studies try to develop a simulation-based automated design processes to integrate building performance simulations in early stage design. They generally

focus on running more simulations in a less amount of time to compare more design alternatives, rapid feedback and visualization of results. These automated processes usually require connecting a few modeling or simulation programs, and coding the geometry. In this way, it is possible to run many iterations, and programs to automatically visualize best alternatives for defined objectives. But, the problem is the processes are still not simple. Users need to interact with more programs, which is also time consuming in terms of setting up the relationship between these programs, etc. Also, the parameters that can be considered at a time are limited for many processes, and the results are not very clear. For instance; the programs run so many iterations and pick the best optimized alternative, but users may not specifically know why it is the best, or which parameter is more effective on that result.

Further, there are some efforts that have focused on using simulation tools to do analysis and support decision making in the building design process from a technical point of view. However, there also is the option to use these tools to help design teams to come up with viable design alternatives. This thesis research intends to explore what role building performance simulation tools can play as design tools, apart from their role as analysis tools, helping the design team to generate building design variants. The aim of this thesis research is to explore and enhance the role of simulation tools from a design point of view in architectural practice.

For this purpose, instead of creating new tools or automated processes, it is planned to develop an approach that could enable building simulations to be used as simpler evaluation tools to consider passive systems integration and optimization in early design phases. With this approach, it will be possible to utilize all of the current building simulation programs' benefits, not specific ones.

1.3 Impact of the Thesis

The public relevance of the development of this methodology will be a contribution that enhances decision-making during the design of energy-efficient buildings. In a general sense, this contributes to increased attention for building performance and helps design teams to respond to the demand for high-quality buildings. The specific focus on selection of passive system integration and optimization in early design phase contributes towards making efficient use of fossil and alternative energy

sources in buildings, and to the overall goal of managing the impact of the built environment on global energy use.

The scientific relevance of the development of this strategy lies in a contribution towards solving the long-standing problem of integration of building simulation into the building design process in early stages.

This project will be of interest to scholars, designers and practicing architects who are interested in high performance sustainable building design. It might also provide guidance to policy makers on how to address passive system integration in energy efficient buildings and how to design effective energy use and comfort goals in policies. To the extent that this work can influence policy makers, the general public will benefit from the implementation of better building design policies.

2. LITERATURE REVIEW

In this chapter, high performance (performative) building design, building performance simulation at the early stages of design; conventional energy performance metrics; resilience measures and strategies in building design; temperature thresholds and output visualization in literature are discussed.

2.1 High Performance (Performative) Building Design

High performance building design, sometimes referred to as performative building design, represents a process that integrates and optimizes all major aspects, such as energy conservation, environment, cost-benefit, sustainability, safety, security, durability, accessibility, productivity, functionality, and operational considerations. High performance building design explicitly establishes performance metrics and indicators that can be used to test the proposed building at the design stage, throughout construction, and after it is occupied and operational (Kesik and O'Brien, 2017).

Key performance parameters are related to health, comfort, energy and water efficiency, carbon footprint, durability, accessibility, flexibility/adaptability, affordability and resilience. Professionals who engage high performance building design seek to attain or surpass performance thresholds that correspond to the environmental, social and economic aspirations of society as a whole, rather than any individual, organization or interest group. A key consideration in the high performance design of housing is intergenerational equity to ensure the housing needs of future generations are not compromised (Kesik and O'Brien, 2017).

Over the life cycle of a building, its use and occupancy can undergo significant changes when the building is re-purposed. Initial energy modeling assumptions about active systems that respond to occupancy and operating schedules may no longer apply. The most persistent attributes are the passive features of the building such as the building form and solar orientation, the overall effective U-value of the

enclosure, fenestration and fixed shading devices, and its 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 prior to introducing active systems. 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).

The findings of related studies indicate that designers seeking to reduce space conditioning loads in multi-unit residential buildings should focus first on building envelope performance parameters (Kemp, 2014). The building envelope and the operation period of the heating system have the largest impact on the total energy consumption of buildings (Manioglu and Yilmaz, 2006). For these reasons, this thesis focuses on the passive design strategies related to building envelope which are briefly discussed in this chapter. But, some of the strategies can benefit to achieve 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) is very significant (Morrison Hershfield, 2011). In a study by Cheung et al. (2005) it is proved both annual and peak cooling loads are reduced more with increased thickness of insulation at any position. Though, 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 multi-unit residential 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. This study assess balcony shading versus adjustable shading devices to determine if the latter can achieve both the passive solar gain and shading benefits.

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, as well as between suites and common areas of MURBs 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 by others, and the results indicated that thermal autonomy was very poor without occupant interaction, and 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).

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 moveable insulation panels (MIPs) indicates significant potential for the application of this technology to energy conservation and enhanced daylighting (Du Montier et al., 2013). It is conceivable 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.

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 these new approaches must incorporate serious consideration of the influence of building occupant behaviour on their effectiveness (Brown, 2015).

In summary, the most effective passive strategies to reduce space heating and cooling energy demands for skin-load dominated buildings are as follows:

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. These passive measures should be viewed as relatively valid, recognizing they are more qualitative than quantitative in terms of observed building performance. There are many reasons cited in the literature that explain why building energy simulations do not always accurately reflect actual energy consumption (De Wilde, 2014). For the purposes of establishing robust default values for passive measures in buildings, it is more practical to be relatively, rather than absolutely, accurate.

In the context of a low carbon economy, this study assumes 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.

2.2 Building Performance Simulation at the Early Stages of Design

Building design is an activity that takes place at the start of the life cycle of buildings. Use of a building can last decades, sometimes even centuries; hence in general design decisions made during the design process will have a long-lasting impact (Müller and Vogel, 1976; Cobuild English Dictionary, 1995).

In the near future, mandatory codes and standards are expected in most of the industrial countries in order to achieve neutral or zero energy built environments (ASHREA Vision 2020, Task 40). Additionally, it is widely acknowledged that the design process of a high performance building is highly complicated. The important challenges in the early stages are combining passive and active systems and guiding designers towards the objective of energy and indoor comfort (Attia, 2012). If building performance simulation (BPS) tools are integrated in the early design phases, informed decision making can be assured in order to design high performance green buildings (Hayter, 2001).

In literature, there are many ongoing efforts to achieve the integration of building simulations to the early design process. Augenbroe (2001) identifies four major approaches towards integration which are still the most common ones in literature:

1. “Automated data transfer”: This approach assumes that the integration problem is mainly a problem of information exchange between a) building designers and their tools and b) building simulation experts and their tools. Automated data transfer tries to solve this problem through the development of interoperable tools and use of one shared building model.
2. “Consultant taking care of integration”: The design team includes simulation experts, and interaction between designers and simulation expert is necessary.
3. “Re-development of simulation tools to prevent the integration problem”: This approach aims to develop new modular simulation tools that are geared towards communication with the building design team.
4. “Minimalistic data-transfer through process-context sensitive, lightweight interfaces”: This approach supposes that automated data exchange only makes sense if the process context in which simulation takes place is taken into account. Since all simulations have a purpose to analyze building

performance, full interoperability in which all data is accessible for all tools and results in excessively complex interfaces and redundant data transport between building product model and tools. The solution for this is believed to be capturing of the process context in scenarios in which analysis efforts can be embedded.

Note that these approaches do not appear to fully address all the integration problems of building simulation into building design process. Automated data transfer comes with the problems of lack of trust in simulation results, and assumes that one universal model can be developed that can be used to analyze all building designs. Consultants taking care of integration still need to find suitable tools and models, and have to operate those within the available time and money. Re-development of simulation tools will still have to deal with the problem of having sufficient expertise in the design team, as well as getting the team to trust in results, in order to be successful; minimalistic data-transfer still has to build the same trust in the results (Wilde, 2004).

In the traditional architectural design process, building performance evaluation is usually done by an expert who is mostly an engineer. Also, available simulation tools are typically based on expert knowledge necessary to input the data needed, run the simulations and interpret the results. Mostly, architects are non-experts in that area and they do not know about precisely every parameter necessary to run a building performance simulation. But they are the ones who have control on form, materials and technical systems of the building design. This information can be used as input to assess building performance in early design phases (Schlueter & Thesseling, 2009).

From this point of view, there is a need for an approach that could enable building simulations to be used as simpler evaluation tools in early design phases. With this modeling approach, it should be possible to utilize all of the current building simulation programs' benefits, not only specific ones. It should ideally offer a process that is manageable for both architects and engineers. It must be far less complex and difficult than the comprehensive energy modeling of buildings conducted at present. Performance assessment for the early design stages should use intuitive parameter inputs, indicators and metrics such that critical decisions can be made at the conceptual design stage, quickly and effectively. The results must be

meaningful to persons who may not be specialists in energy simulation or similar analysis work. Another important aspect is the visualization of the results. For fast and intuitive understanding, suitable graphical visualisation has to be applied. In a study by Schlueter & Thesseling, 2009, it is proved that intuitive visualization of the results is very important for easy and quick interpretation (Schlueter & Thesseling, 2009).

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 et al. 2016). It also remains unclear how to effectively apply the many sustainability and resilience metrics for buildings (Marjaba and 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 are only beginning to address issues of climate change and resilience (Lomas and 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 et al., 2012). It is beyond the scope of this thesis to address all of 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.

2.3 Conventional Energy Performance Metrics

In order to study how well a design will perform its function or role, one must qualify and quantify its performance. Based on the quantification of performance of all design alternatives a decision must be made to select the design option that has the variety of outcomes that are most preferred.

Building performance simulation, mostly consider energy-related issues so far and building energy simulation generally focus on the thermal aspects in buildings; such as, energy consumption, heat flows and temperatures (Clarke, 2001).

The most commonly used metric to evaluate the results of energy simulations is energy use intensity (EUI). It corresponds to a combination of all fuel types used by a building in a year, normalized to building size (in square feet of floor area).

This metric is easily understood, but there are a number of questions if this is the most suitable metric for building performance. Building use type, climate and hours of use in buildings affect EUI significantly. For instance, two buildings located in two different climates will naturally have different EUI (all other things being equal). So in such cases the comparison of EUI does not certainly indicate conclusions about building performance between different buildings (Frankel et al., 2015).

However, individual building performance over time can be tracked using EUI. Also, comparison of EUI can be helpful if the predicted performance variables (such as climate, building uses, hours of operation and occupancy) are normalized to indicate different building features. In this way an EUI can be used as a benchmark or target for building performance (Frankel et al., 2015). Because of its simplicity, EUI is used widely in the market. But it is clear that, it can be count as an appropriate analysis metric for later phases more than early on phases.

Another common metric is the Zero Energy Performance Index (zEPI). The reference point is normalized to a value of 100, while a building with net zero energy use is set at a value of 0. The zEPI score identifies building performance on this 100 to 0 scale.

Energy Star uses a relatively different metric which identifies a percentile score compared to CBECS data. EUI is normalized based on building use, occupancy and climate, then this value is plotted against the CBECS's building stock in percentage. A 100 is the highest achievable score and corresponds to a building performing in the top 1 percentile of the overall building stock.

There are some other energy metrics that have not gained widespread use, yet. These metrics mainly comprise building use patterns, for example; energy use/occupant and energy use per occupied hour. Even though they may signify valid reflections of building performance, occupancy and use variables limit the applicability of these metrics because they are extremely difficult to track in real time.

Apparently, the most commonly used energy performance metrics at the building level rely on energy use for heating, energy use for cooling, overall energy use and

building overheating (Wilde and Coley, 2012). There are also a number of non-energy metrics that 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 et al., 2015). For example, in a study by McGilligan et al., adaptive comfort degree-days, as a temperature difference/time composite metric, has been developed to better assess energy consumption under changing climate conditions. The aim of the metric has been proposed as providing 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 et al. 2011). Another study, by Lomas and Ji, resiliency of passively cooled buildings is linked to their life-expectancy which decreases with heat gains and the warmth of the locality (Lomas and Ji, 2009). And, the authors argue that resilience to climate change, susceptibility to internal heat gains and the impact of future heat waves, should be an integral part of building design. Both studies extensively discuss available guides and standards for defining thermal comfort metric, and suggest relating interior comfort to outdoor temperatures directly. They also expose that more research in creating adequate comfort metrics for free running buildings is required.

In a study by Levitt et al., it is stated that metrics for quantifying energy consumption so far focus on the role of mechanical systems rather than architecture (Levitt et al., 2013). Any of the existing metrics tell us little about how a building design might perform without mechanical systems input.

The idea of this thesis uses a new metric called “Thermal Autonomy”. Levitt et al. uses this metric to measure “how much of the available ambient energy resources a building can harness rather than how much fuel heating and cooling systems will consume” (Levitt et al., 2013). The concept of Thermal Autonomy had been used by Levitt et al. for the design of a classroom in Oakland, California to show how a typical classroom would perform without heating or cooling systems. And, the metric for that study had been defined as “the percent of occupied time over a year where a thermal zone meets or exceeds a given set of thermal comfort acceptability criteria through passive means only”. They concluded that “thermal autonomy might be a useful way of defining building performance for a given climate and program”. The

authors also suggested further research that focus on thermal autonomy analysis for different buildings in different climates over a large sample size and comparison of these thermal autonomy numbers to Energy Use Intensity for a greater understanding of both metrics. And, this thesis aims to fulfill these research questions.

More recently, resiliency metric has been used to the buildings as well. Resilience is the capability of a building or community to adjust to changing circumstances and to maintain functionality and strength in the face of extreme weather events or other conditions (Kesik, 2015). Building characteristics and operational features can affect their habitability during a power failure or other events. As a scope of this thesis, the developed approach will also enable the designer to assess the passive survivability of the building, as a resilience measure, when events such as electrical power system failures occur for extended periods during extreme weather conditions. The concept of resiliency in building design is discussed in detail below.

2.4 Resilience Measures and Strategies in Building Design

The world is entering an age of climate change where people are witnessing an increased frequency and severity of extreme weather events. Aging municipal and energy infrastructure has rendered many communities vulnerable to flooding and power disruptions. While these extreme events are seldom unmitigated disasters, they have the potential to disrupt our day-to-day lives, business operations, and possibly jeopardize human safety, private and public property.

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. It is also important that buildings can withstand exposure to extreme conditions without suffering serious and/or permanent damage.

Resilience is not a new concept in building design and in the past it formed the basis of so many of our building traditions, whether it was to ensure people survived a long, harsh winter or a dry, hot summer (Kesik, 2015). Before they became dependent on

the energy grid, houses were heated with wood, cooled by porches and natural ventilation, and illuminated by windows and candlelight.

The resilience of multi-unit residential buildings is largely determined by the performance of the envelope. Robust envelope design ensures that buildings are durable, energy efficient, comfortable and also provide shelter under extreme conditions. Under both normal and extreme conditions, the building should not experience performance problems that can compromise secure shelter or devalue real estate investments.

There are many strategies available to enhance the resilience of multi-unit residential buildings. Most of them are simple and relatively inexpensive. For example; 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 reduce space heating and cooling energy demands 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, 2017). 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 be likely to provide better habitable conditions during winter and summer blackouts.

In another research, passive cooling techniques are presented by Santamouris et al. 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 warmest climates. Furthermore, the authors suggest 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.

Tornadoes, hurricanes, record rainfalls, ice storms, droughts, heat and cold waves are among the extreme weather events that will challenge the resilience of building enclosures. Building enclosures comprise assemblies and components of buildings, such as the foundation walls and slabs, the above-grade walls and windows, and the roof, in order to provide a desired degree of separation between the indoor and outdoor environments. 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, increasing a building's "passive survivability" (Schoeman, 2015).

Resilient envelope also incorporates measures for thermal autonomy and passive survivability. Housing is a very special type of building because people expect it to provide some measure of shelter against the elements. Thermally inefficient enclosures that cannot respond properly to solar gains and afford natural ventilation can quickly become too cold during extreme winter weather and too hot during summer heat waves, forcing people out of their homes. This is particularly problematic for the elderly and the ill, especially if they do not have a support network of family and friends -and the situation is further exacerbated if people are economically disadvantaged. Thermal autonomy and passive survivability are two related and critical metrics for the resilience of MURBs. 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 and safety, resilience, and the time-based metrics of thermal autonomy and passive survivability, 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.

2.5 Temperature Thresholds

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 the Fanger 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 et al. 2013). However, if the decision is being made on a different analysis principle, for instance the use of degree hours for the air temperature, then there would not have been a need to include any occupant and occupant properties, and the treatment of surfaces might have been different. (Wilde 2004). In addition, 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 ASHRAE Standard 55 (ASHRAE, 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 and below 10°C in that model. Since the mean monthly outdoor dry-bulb temperature would be less than 10°C in Toronto and Vancouver in winter, this comfort model may not be used for winter months in this study. On the other hand, a standard “Memorandum HTM03-01” (DoH, HTM03-01, 2007), which is concerned with ‘specialist ventilation for healthcare premises’, offers a range of acceptable internal dry-bulb temperature, which is quoted as 18 °C to 28 °C ‘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 health care spaces, especially for identifying the risk of overheating in summer. They recommend CIBSE Guide A (CIBSE Environmental Design, 2006) for that purpose. For naturally ventilated buildings, the Guide notes that ‘during warm summer weather 25 °C is an acceptable indoor operative temperature’ (see e.g. CIBSE Guide A). Since no more specific guidance for naturally conditioned spaces is currently available in the literature, comfort levels of 18°C and 25°C operative temperatures for thermal autonomy analysis are employed in this study. At the same

time, the exact threshold is not the focus of this study. The relative performance of the designs may be evaluated by using any reasonable comfort range with the process suggested in this thesis.

For passive survivability 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 for the heating period. The 30°C upper threshold is consistent with other health standards (e.g., the United Kingdom Health Service, 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 and Wilson, 2016). This approach predicts a 25% chance of severe heat stress at dry-bulb air temperatures lower than 30°C when the relative humidity 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 et al., 2013), hence the passive survivability thresholds deployed in this thesis may be considered to be reasonable and manageable until such time as better public health guidance becomes available.

2.6 Output Visualization

For the pursuit of high performance green building design, it is important to understand the processes engaged and control them. To understand the processes, their inputs and outputs should be specified, and the relationship between the associated properties should be identified. For this reason, development of graphical design feedback methods is very critical for this study. Furthermore, a major problem with current simulation approaches is that most of them request extensive input data (Ochoa and Capeluto, 2009) and they provide vast quantities of data output (Attia et al., 2013). On the other hand, 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 et al., 2006), something that is currently unknown to most architects.

In literature, the visualization tools mostly use simple lines, columns and bar charts to display the energy usage patterns over time for buildings (Yarbrough et al. 2014). In a study by Attia et al. (S. Attia et al., 2013) 28 researchers, who are experts in optimization and building simulation, are interviewed to assess gaps and demands for integrating building performance simulation tools in net zero energy buildings design. One of the questions was “Do you have graphical user interface for your own optimization tool? And which kind of output analysis visualization did you do using optimization tools?” Results showed that most interviewees convert the output data using different processing tools, such as DView, Excell, gnuplot or writing scripts in MATLAB, in order to interpret output results. The figure 2.1 demonstrates the 14 most used output analysis graphs. Overall conclusion is that each respondent had his or her own custom visualization techniques (Attia et al., 2013).

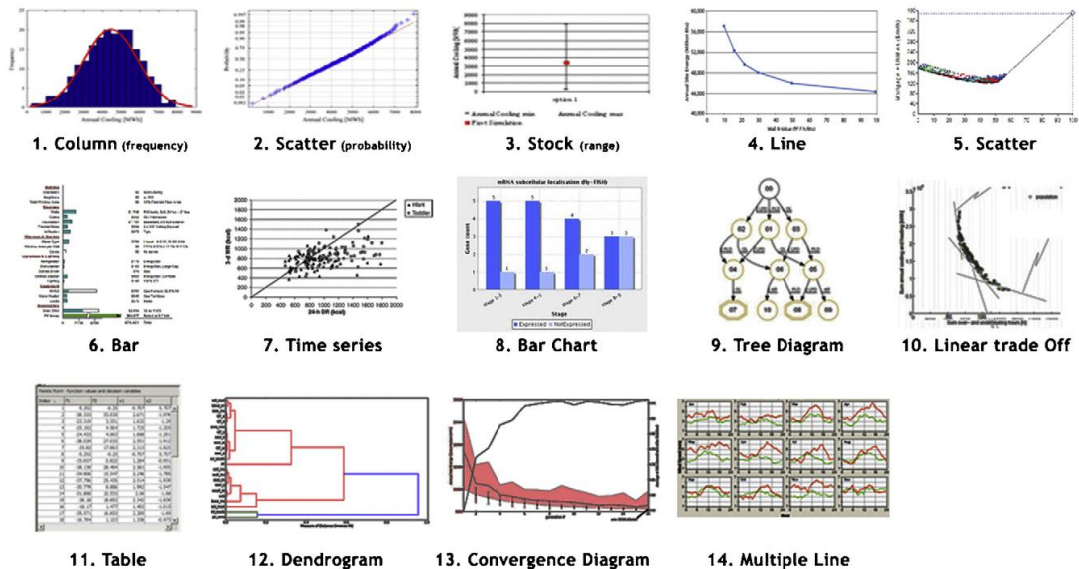


Figure 2.1 : The most used output analysis graphs in building performance simulations (Attia et al., 2013).

The main purpose of visualization tools is to provide comparable energy usage data over time. For example, The Pulse Dashboard (Pulse Energy, Vancouver, British Columbia) and iBEnergy Software suite (Quality Attributes, Ames, Iowa) provide energy consumption data for each commercial building by using 2-D trend line. Building Dashboard (Lucid, Oakland, California) and Energy Efficient Education Dashboard (Quality Automation Graphics, Ankeny, Iowa) deliver information about energy usage based on short-term measurements from meters using 2-D columns. Other visualization tools aim to understand energy consumption of different

buildings in the same region. For example, a visualization model was built by Howard et al. which showed the estimated annual energy (kW h/m² floor area) at the individual building level in New York City. At a study by Yarbrough et al. (Yarbrough et al., 2014) a new visualization tool was developed on the campus level to understand the relationship between individual building peak demand and the campus peak energy use (McCusker, 2013). That tool used color mapping to illustrate building energy consumption and GHG emissions at the University of Massachusetts Amherst. However, none of the above-mentioned models or tools are intended to expedite decision-making in early design stages.

Another effective visualization method is the Sankey diagram (Schmidt, 2008) which can be used to represent materials and energy flows. Sankey diagrams use arrows in different widths, where the width represents relative degree of flow and the direction implies the relation between sources and sinks for each flow. These diagrams can be used both for visualizing performance of existing systems and during the design process using modeling and simulation. Some of the design and simulation tools use Sankey diagrams for visualizing predicted energy use, for example CASAnova software (Heidt, 2012) and Sefaira (Sefaira, 2012). They show values for infiltration and heat transfer between spaces but the non-expert users may not understand whether these values are “good” or “bad” (Abdelalim et al., 2016).

In early design stage there is significant value in identifying the strongest parameter interactions by using clear and understandable graphics. In literature, “Wheel of Interaction” and “Lines of Influence” are valuable graphical applications to understand interactions, which were reported by O’Brien et al. (O’Brien et al., 2008). In the Wheel of Interaction, the parameters are plotted around a circle to show the interactions, and they are joined by a line to specify their strength. Figure 2.2 (left) is an example in which demonstrate the strength of interaction between south-facing window-to-wall ratio (WWR1) and the other parameters. This can give the designer an idea if this change has a significant impact on the design (O’Brien, 2011). Figure 2.2 (right) shows all parameter interactions simultaneously.

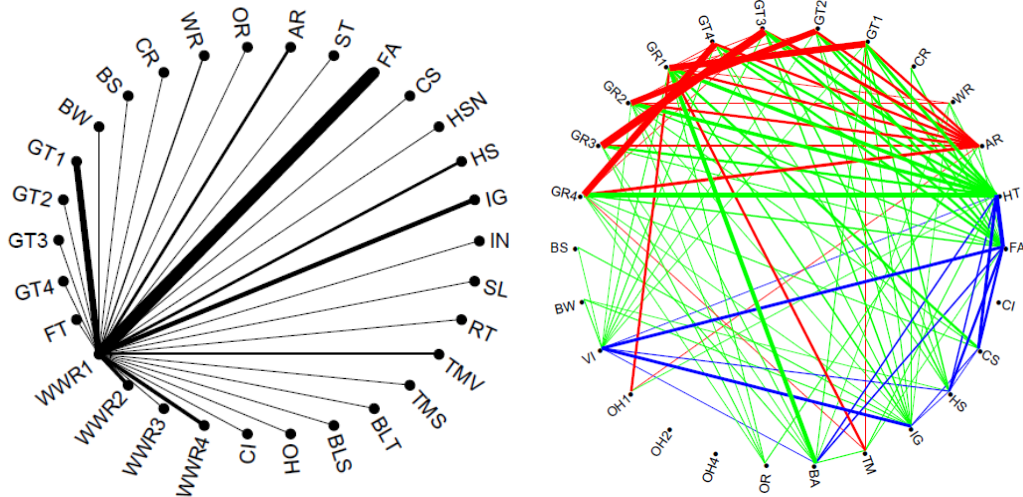


Figure 2.2 : Example of the “Wheel of Interaction” graphical application.

In simulation-supported design, applying parametric analysis to one or more parameters is one of the most common approaches. O’Brien (2011) uses Lines of influence as “a display of curves for performance (one of several metrics) versus the range of one or more parameter values”. Examples are shown in Figure 2.3. Both Lines of Influence and Wheel of Interaction are useful when multiple parameters are compared.

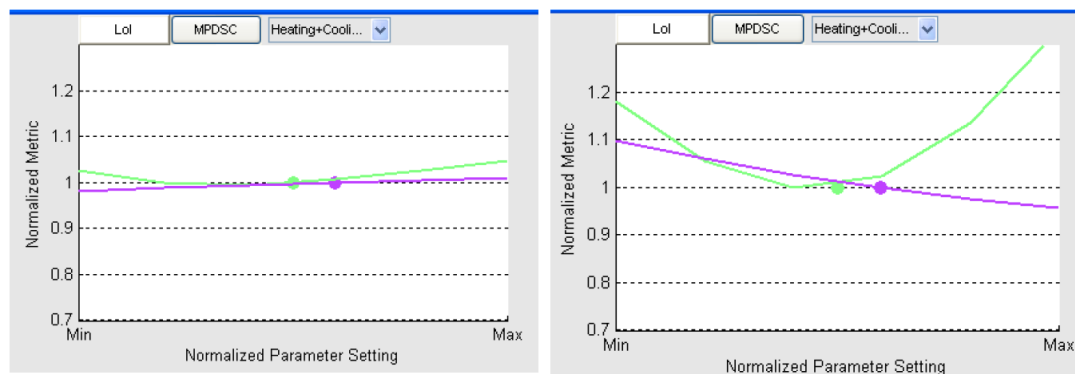


Figure 2.3 : Example of the “Lines of Influence” graphical application.

In many conventional building simulation tools the results are presented for total of year and day or a specific time. However, the annual variation in performance is also valuable information. In 2003, Spatio-Temporal Irradiation Maps (STIMAPs) are introduced by Mardaljevic which are surface graphs present the year on the x-axis and the day on the y-axis (Mardaljevic 2003). These graphs show the temporal variability of performance in a very dense format with continuous annual data. “Temporal maps are an intuitive and powerful way in which to view an entire year’s

worth of thermal analysis in one glance” (Kleindienst et al, 2008). Figure 2.4 shows an example of the “Temporal Map” concept with the comparison of two cases. In this thesis, the “Temporal Maps” are used to visualize the hourly data by using carpet plot technique which is exemplified in Figure 2.5.

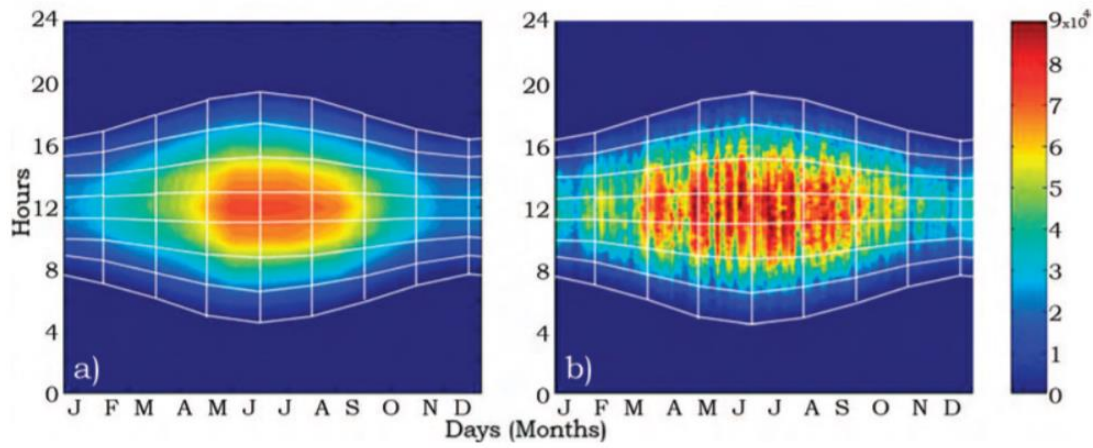


Figure 2.4 : An example of comparison with temporal maps.

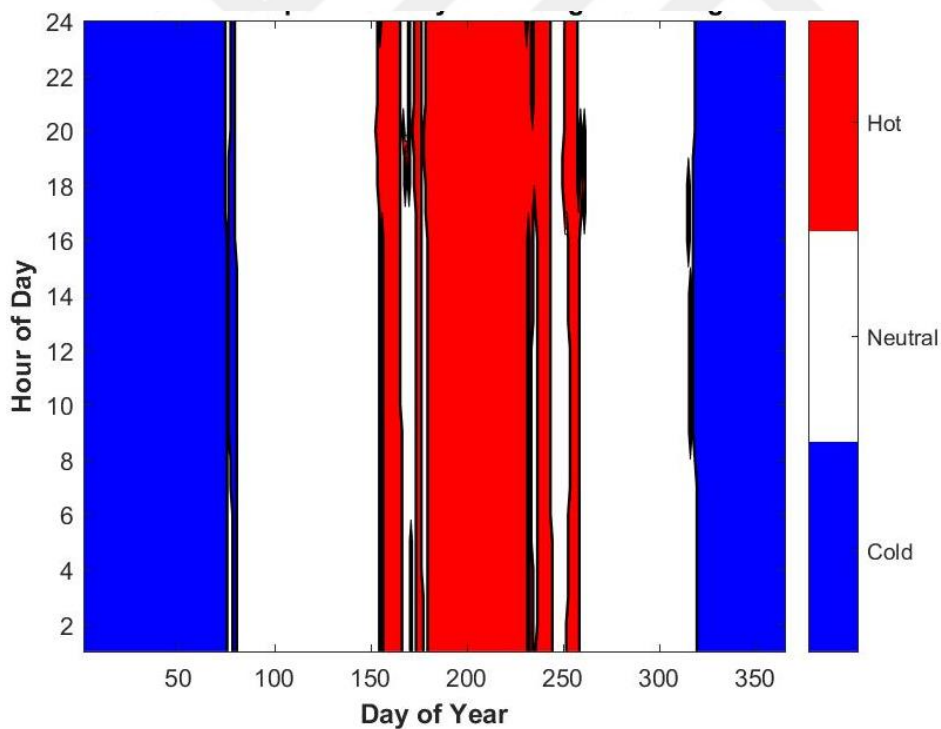


Figure 2.5 : A carpet plot showing the thermal autonomy with the periods that are cold, neutral, and hot indicated for each out of the year.

2.7 Conclusions

Based on the literature review a brief summary of the substantial observations are listed as follows:

- Building performance simulation that effectively informs early stages of design is critical to achieving sustainable and resilient buildings.
- The passive measures relating to the building envelope design make the greatest contribution to energy efficiency, comfort, daylighting, thermal autonomy and passive survivability.
- There are sufficient simulation tools to advance passive design but there is need to standardize the methodology and metrics so that architects are informed at the early stages of design in a timely manner that is time and cost efficient.
- The visualization of the time-based metrics, in an intuitive and powerful way, are effective means of intelligently selecting robust passive measures.
- The future work will be to develop correlations between simple passive performance metrics and performance levels so that researchers, practitioners and policy makers have reliable indicators that can be applied to achieve code compliance.



3. A NEW APPROACH TO IMPROVE PASSIVE PERFORMANCE OF BUILDINGS THROUGH THE TIME-BASED BUILDING THERMAL RESILIENCE METRICS DURING THE EARLY STAGE OF DESIGN

As stated earlier, this thesis mainly provides 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 and passive survivability.

3.1 Time-based Metrics of Thermal Autonomy and Passive Survivability

In this thesis, thermal autonomy (TA) is used as a *measure of the fraction of time a building can passively maintain comfort conditions without active system energy inputs*. In equation form, it is expressed by the author as:

$$TA = \sum_{i=1}^{8760} \frac{[T_{op} \leq T_{min}] \wedge [T_{op} \geq T_{max}]}{8760} \quad (3.1)$$
$$TA = \sum_{i=1}^{8760} \frac{[t_{comf,i}]}{8760}$$

Where is $t_{comf} [T_{min} \leq T_{op} \leq T_{max}]$ (T_{op} within the comfort range)

Where $T_{op}(t)$ is the indoor operative temperature, 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.

Passive survivability (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 and Bennet, 2016). PS is a tool to help ensure that buildings will be less susceptible to becoming unlivable in the event of extended power outages or other system failures during extreme weather periods.

3.2 Types of Simulations and Analysis in the Approach

The EnergyPlus simulation engine was chosen for the study because it is a well-developed and well-documented, validated analysis tool that is widely used by researchers and practitioners (EnergyPlus, 2014). Also, the straightforward, user-friendly graphical interface DesignBuilder was used to perform 792 parametric simulations reliably and efficiently (DesignBuilder, 2014). For each unit configuration, based on four different orientations and two window-to-wall ratios, three types of simulations are conducted to test 11 cases in three different climates. The three simulation types are defined as following:

1. Passive parameters are assessed through annual space heating and cooling energy use intensity ($\text{kWh/m}^2\cdot\text{year}$). Note that energy use intensity (EUI) herein refers to the space heating and cooling energy (with COP of 1) only.
2. The systems for HVAC, lighting and equipment are turned off in the model for thermal autonomy 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.
3. For passive survivability 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 passive survivability. 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 suggests that moisture may become apparent for sedentary, lightly clothed people as operative temperatures rise above $26\text{--}28^\circ\text{C}$. *“Thus, for most practical purposes, the influence of humidity on warmth in moderate thermal environments may be ignored.”* (see CIBSE Guide A). However, recent work on overheating (Holmes, Phillips and

Wilson, 2016; Anderson et al., 2013) points to the need to carefully consider 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 criteria, or any other possible comfort criteria. The aim of the study underlying this thesis is developing a manageable visualization approach for analysing robust passive measures through the time-based metrics of thermal autonomy and passive survivability.

3.3 Development of the Visualizations for Thermal Autonomy and Passive Survivability Analysis

The TA graphs are created in Ladybug tool, which is a plugin for Grasshopper. First, the indoor temperature data for each case is exported from DesignBuilder in an excel file format. Then, this file is read in Ladybug, and visualized by using the example coding pictured in Figures below. Figure 3.1 shows how the excel file is imported and read by Ladybug tool in Grasshopper. Figure 3.2 pictures the coding required for the legend, titles and colors. And, how to define the temperature thresholds in Ladybug, Grasshopper is showed in Figure 3.3.

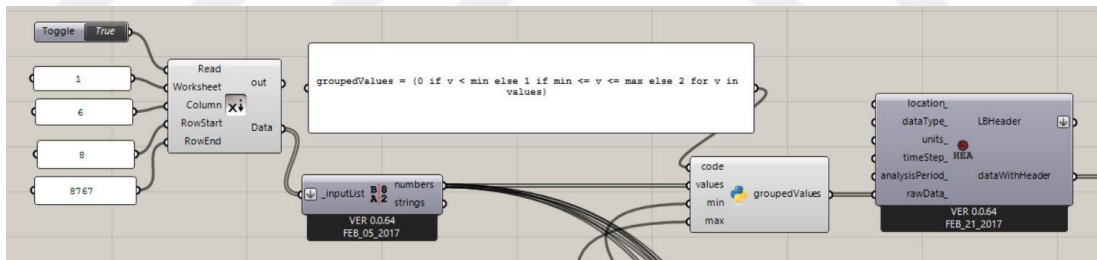


Figure 3.1 : Import and read excel file in Ladybug / Grasshopper.

For PS graphs, the indoor temperature data is exported from DesignBuilder in an excel file format and plotted in MATLAB. The coding for PS graphs is presented in Appendix D.

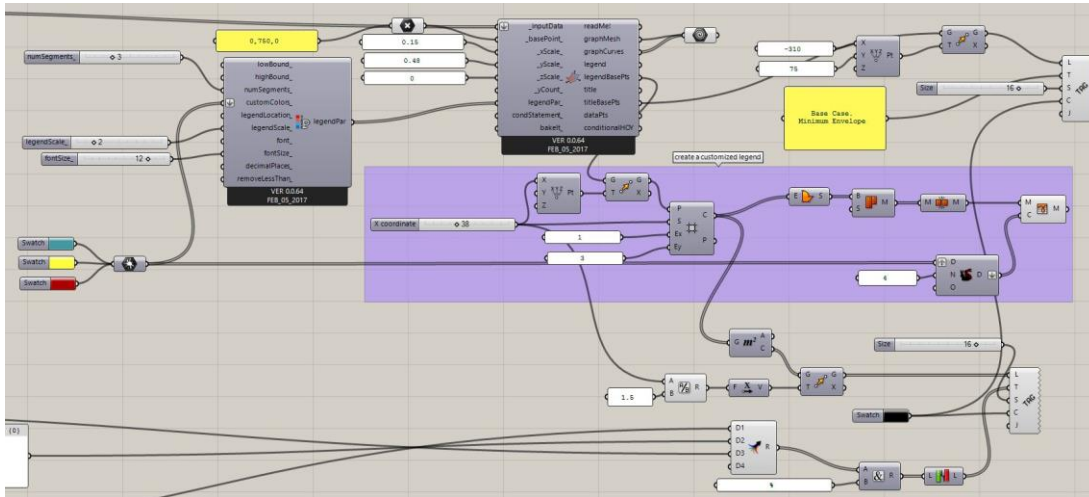


Figure 3.2 : The coding required for the legend, titles and colors.

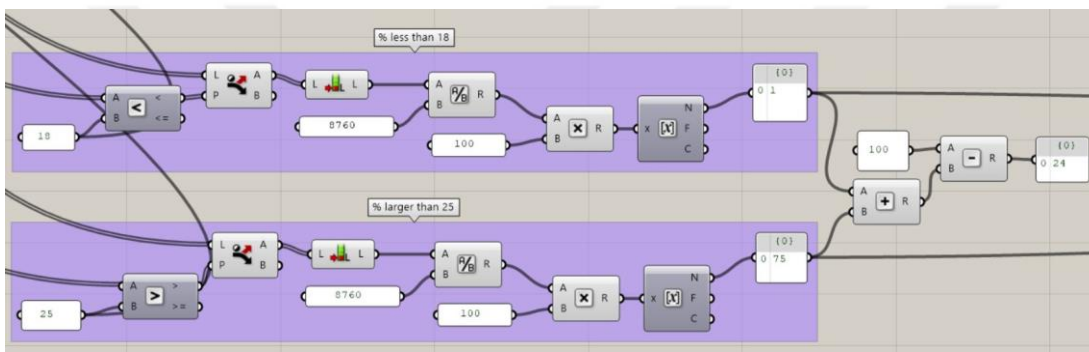


Figure 3.3 : Define the temperature thresholds in Ladybug / Grasshopper.

In design of the graphs affordance theory is followed in which visualization design can be evaluated and compared (Gibson, 1977). Based on this theory, good visualization should be clearer, easier, and faster for the user to identify target information/patterns. To improve affordance in this study, compact design is applied to minimize the cost of visual searches, for faster pattern seeking (e.g. yearlong data in one bar). Further, pre-attentive processing is taken advantage of with line continuity that captures the attention of the user almost immediately (Treisman, 1985). The human eye is believed to have evolved to subconsciously capture movements and discontinued lines (Ware, 2013). Also, colours at very different wavelength are expected to be perceived very differently due to cone sensitivity variations (Healey, Booth, & Enns, 1996). This can lead to better processing time (e.g. warmth of the colour to sense of temperature). Additionally, the focus in PS graphs provides distinct spatial texture on the figure so that passive survival thresholds can be easily identified (Ware, 2013).

This research claims that TA graphs indicate how a building design might perform independently from mechanical systems and they give an idea of when or if mechanical systems can be turned off. TA graphs show daily and seasonal patterns and predict occupant comfort. Further, they are effective in visualizing building-level passive design strategies and have temporal resolution that is sufficient to understand the building's energy performance. Overall, they are useful for facilitating passive systems design decision making because they are intuitive. Likewise, PS graphs are aimed at indicating how a building design might perform independently from mechanical systems. They predict occupant comfort and they are effective in visualizing building-level passive design strategies. PS graphs have temporal resolution that is sufficient to understand the indoor comfort conditions during extended power system failures. They are also useful for improving resilient design decisions because they display information at a human scale with a familiar metric: temperature.

3.4 Survey Study to Assess the Effectiveness of the Visualizations

A 35-question online survey was conducted, using Google Forms, to assess the effectiveness of visualizing the time-based metrics of Thermal Autonomy and Passive Survivability in building performance simulations. In total, 65 valid responses were collected from architects, engineers and educators from a population of approximately 500 individuals contacted by email.

In this chapter, first, the survey questions are briefly described. The detailed survey questions can be seen in Appendix A. Then, the results of the survey are discussed with the aim of answering the following questions:

1. What are the participants' attitudes about using building BPS tools and visualizing data?
2. What are the participants' knowledge of common energy performance metrics in current practice?
3. Do the participants' feel that proposed thermal autonomy graphs are suitable for interpreting output of simulations appropriately?
4. Do the participants' feel that proposed passive survivability graphs are suitable for interpreting output of simulations appropriately?

5. What is the participants' opinion about the use of current and proposed metrics and their suggestions for future work related to time-based metrics?

Finally, the results of the survey and resulting analysis are discussed to inform designers, researchers, software developers, and building standards developers about the effectiveness of time-based metrics on improving the building energy metrics that inform building design, particularly at the early stages of design.

3.4.1 The survey questions

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 where they wished to share further insights. The survey questions were separated into five categories:

1. Background information: Participants are requested to tell about their profession, country, experience with building energy related work, the frequency of building energy performance related work in their practice, and tools and methods they used for visualizing building performance data.
2. Knowledge of common energy metrics: A graph was provided to demonstrate a common use of energy metrics in current practice. Participants were asked how familiar they are with the metrics and units presented in the graph and how useful they find them for making decisions about mechanical systems and passive design decisions related to the building envelope.
3. Interpreting proposed thermal autonomy graphs: A short explanation of thermal autonomy concept and an example visualization of TA is provided and the participant's understanding of the graph is tested with related questions. Then, their opinion is asked about the facts claimed in this thesis using five-point Likert-type scale of *agree* to *disagree*.
4. Interpreting proposed passive survivability graphs: A short explanation of the passive survivability concept and an example visualization of PS was provided and the participant's understanding of the graph was tested with related questions. Then, their opinion about the facts claimed in this thesis was asked using five-point Likert-type scale of *agree* to *disagree*.

5. General Questions: After the participants had an opportunity to compare conventional energy performance metrics [peak energy demand (kW), annual energy consumption (kWh) and energy use intensity (kWh/m².year)] and time based metrics like Thermal Autonomy and Passive Survivability, they were asked which metrics they find the most useful and what suggestions they have for future work related to time-based metrics.





4. IMPLEMENTATION OF THE APPROACH FOR AN APARTMENT UNIT IN THREE DIFFERENT CLIMATES

The thesis is based on the development of 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 and passive survivability. In order to test the applicability of the proposed approach in this thesis, three distinct climate zones are selected and they are discussed in this chapter. Then, specific parameters are identified based on the climate and location characteristics to perform simulations. And, the most critical passive strategies considered by using the proposed approach. Finally, the demonstrative results are analysed through the thermal autonomy and passive survivability metrics in this chapter.

4.1 Selected Climate Zones for the Implementation of the Approach

The selected climates for use in the simulations: Toronto, Ontario, Canada (ASHRAE Climate Zone 6); Vancouver, 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 and the average winter temperature is -4.6°C . The *climate* of *Vancouver* is a moderate oceanic *climate*, that is warm and temperate. The winter months are much rainier than the summer months in Vancouver, which are typically dry, often resulting in moderate drought conditions, usually in July and August. In Vancouver, the average annual temperature is 9.9°C . Adana has a typical Mediterranean climate. Winters are mild and wet and summers are humid and dry. The average annual *temperature* in *Adana* is 19°C . Figure 4.1 graphically depicts a comparison of the three climate zones.

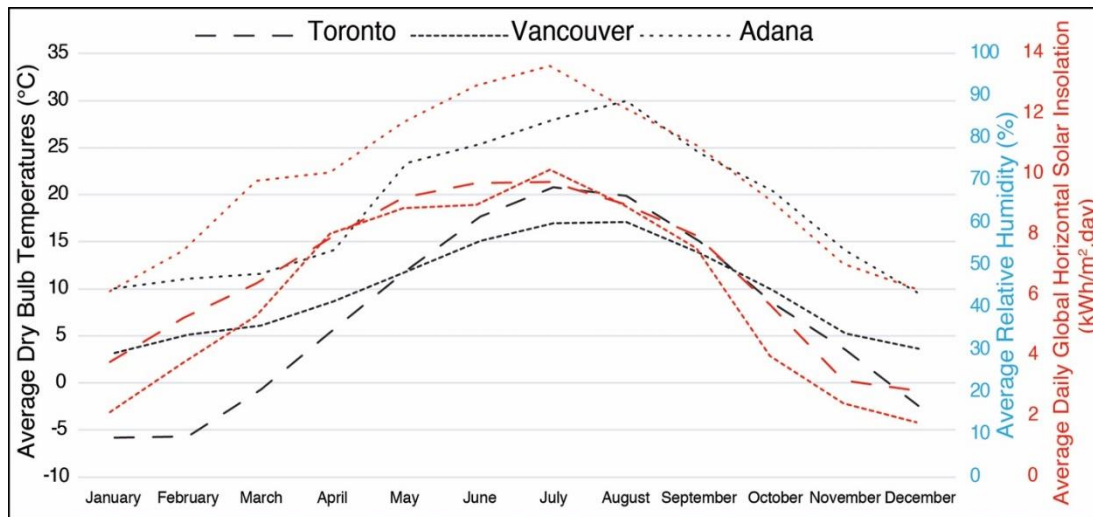


Figure 4.1 : Comparison of dry-bulb temperature, relative humidity and solar radiation for Vancouver and Toronto, Canada and Adana, Turkey.

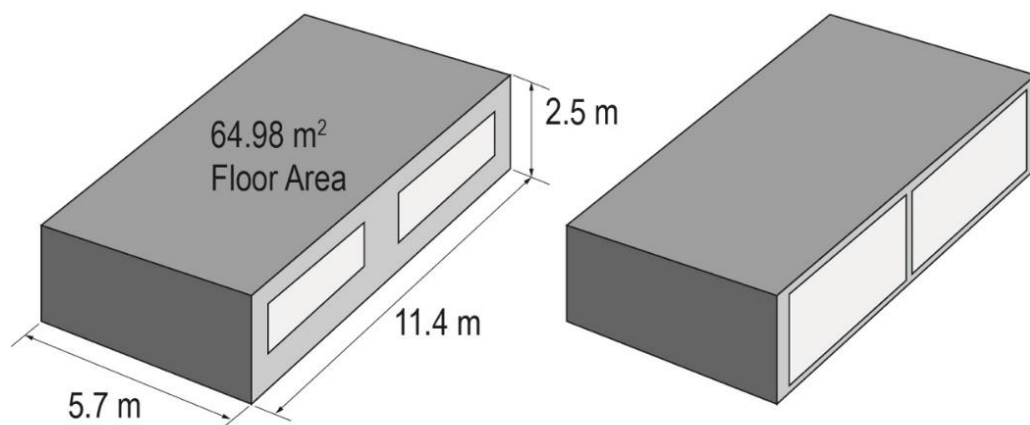
4.2 Selected Parameters to Perform Simulations

In all three climates, the predominant building type used for the construction of apartments consists of a reinforced concrete frame where the shear walls are used to separate suites adjoining a double-loaded corridor or central core. The majority of suites have single aspect facades except for corner suites that have exterior walls on two sides, and are typically single story. The provision of cantilevered balconies is optional and most of the buildings employ window-wall glazing systems with high window-to-wall ratios (>80% or 60%). In this study, the average size of a unit is considered as 70 m² (756 ft²) with an aspect ratio of 2x1(width to depth). According to Urbanation, the average size of a condo in the Greater Toronto Area (GTA) is 70 m² (756 ft²) taking into account bachelor, 1-bedroom, 2-bedroom and 3-bedroom units (The Canadian Press, 2015). This also includes micro-condos which range between 25 to 35 m² (270 to 375 ft²) (Topping, 2014). Unit heights are assumed to be 2.5 m including the thickness of a single floor slab (i.e. half thickness for ceiling and half thickness for floor attributed to internalized units). The floor consists of a 10 cm (4") slab of concrete. The floor area of a unit is 64.8 m² and gross exterior wall area is 28.5 m². Units are located on intermediate floors with no heat transfer across ceiling, floor or adjacent walls because the neighboring units are assumed to be at a similar temperature and represent adiabatic boundaries. The parameters set out in Table 4.1 were applied to an exposed facade depicted in Figure 4.2.

Table 4.1 : Parameters and corresponding values to perform energy simulations.

Orientations			South, West, North, East		
			Low WWR		High WWR
Window-to-Wall Ratio WWR (%)		Toronto, Vancouver	40		80
		Adana*	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
	Solar Heat Gain Coefficient SHGC		High 0.45	Medium 0.35	Low 0.25
	U-Value (W/m ² .K)	Adana	2.700	1.700	1.000
	SHGC		High 0.53	Medium 0.47	Low 0.3
* Excessive solar heat gains in Adana, Turkey climate zone demand smaller window-to-wall ratios than Toronto and Vancouver, Canada. SHGC corresponds to U-values of commercially available sealed glazing units for windows.					

Typical apartment suites are modelled as discrete units with only the glazed facade responding to heat transfer. All five of the other enclosing surfaces are considered adiabatic.



Exposed facade area of 28.5 m² modelled across a range of window-to-wall ratios with the lower bound corresponding to acceptable daylighting apertures.

Figure 4.2 : Characteristics of typical suites used in parametric simulations.

The window-to-wall ratios (WWR) 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 are 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 an upper value 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 modeled based on different occupancy pattern in two countries. In Toronto and Vancouver, Canada, the predominant occupant use of units occurs from 6 PM to 9 AM daily, whereas, in Turkey units are typically occupied all day and only the density of people changes at certain times of a day. For example, childcare is usually provided at home by grandparents or nannies who visit the house daily, or it is common that family members live with elderly parents/relatives who does not have a job and leave their apartments during the day. Accordingly, custom heating and cooling schedules are modeled for different locations as well.

To validate the correlation of the time-based metrics with annual heating and cooling loads, simple HVAC systems are modeled using ideal loads, fuel consumption is calculated from loads using seasonal efficiencies. A COP of 1.0 for HVAC systems was used in order to estimate demands without the influence of energy conversion efficiencies. Mechanical ventilation rates conform to minimum code requirements and were not provided with heat recovery. Natural ventilation and infiltration air flow rates are calculated based on opening and crack sizes (medium), buoyancy and wind pressures. Annual average infiltration air change rate is 0.025 ach for default cases. When natural ventilation is provided that air change rate reaches up to 0.67 ach. These rates are consistent with the literature that examined airtightness and ventilation in contemporary condominium buildings (Finch et al., 2009).

4.3 Selected Passive Strategies to Test the Applicability of the Approach

Passive systems design begins with building form and orientation, and for mid-rise and high-rise housing typologies, the layout and arrangement of suites. Enclosure design responds to this organization of suites according to solar orientation and within the context of climate and weather. Enclosures must manage precipitation, heat, air and moisture to deliver durability, efficiency and comfort while providing views and access to light and air. In increasingly critical consideration is for enclosures to be more resilient in view of climate change and provide secure shelter through extreme weather events. This thesis highlights the most critical considerations for enclosures such as: air leakage, thermal bridging, influence of window-to-wall ratio, balcony thermal breaks and balcony enclosures, thermal insulation, daylight (shading) and natural ventilation.

Air leakage is controlled through the provision of a continuous, structurally supported air barrier system. Attention to detailing at transitions between materials, components and assemblies is essential. Air barriers control air leakage that can lead to moisture problems due to condensation, and it also conserves energy by reducing infiltration. Moisture management involves the selection and arrangement of materials to minimize moisture build up in walls and roofs, and to promote drying.

While designing for rain control, air leakage and moisture management, it is necessary to provide adequate thermal control for occupant comfort and energy efficiency. This means providing adequate levels of thermal insulation for walls, roofs, floors over unheated spaces, and in basements. The thermal efficiency of windows is even more critical because glazing typically represents the weak link in the building enclosure, especially if the amount exceeds 50% of the gross exterior wall area. As noted earlier, air leakage control is both a moisture and thermal control measure that must be integrated with thermal control to achieve energy efficiency, comfort and durability. Thermal bridging is now recognized as degrading the overall thermal effectiveness of enclosures. In the past, building codes prescribed the minimum amount of thermal control required in buildings, but this only referred to the amount of insulation that was provided. Recent studies have quantified just how significantly thermal bridging reduces the effective thermal resistance of walls, roofs and windows. Practical solutions have been developed and are both readily available and affordable.

The thermal efficiency of the enclosure is largely determined by the thermal effectiveness of exterior walls, which are strongly influenced by the window-to-wall ratio - the area of the windows as a fraction of the gross exterior wall area. Selecting high efficiency windows and limiting the window-to-wall ratio are more cost effective than adding more insulation. For multi-unit residential buildings, the typical range of window-to-wall ratios is between 30% to 70%, however, there are many glass condo towers that have been constructed that exceed an 80% window-to-wall ratio.

Balcony thermal breaks can enhance occupant comfort and energy efficiency for cantilevered concrete balcony slabs. Typically, balcony slabs are constructed without thermal breaks because these are a relatively new and innovative building technology. Today, thermal breaks are becoming increasingly affordable and straightforward to integrate in conventional construction practices. Balcony enclosures not only provide a more comfortable and habitable space, but they also enhance thermal performance as well as provide protection against airborne projectiles.

The typical suite in a multi-unit residential building offers fewer degrees of freedom for environmental control than single family detached housing in terms of access to light and air. Daylighting not only conserves energy, but it can also provide passive solar gains. Contemporary research indicates daylighting is important to human health and well being and from an aesthetic perspective, most people prefer well daylit spaces. In addition to providing adequate daylighting, it is also to control against glare and discomfort due to overheating. External and internal shading devices are essential to providing comfort and energy efficiency. Climate change is generating a significant increase in the frequency and severity of extreme weather events. High winds can result in damaged or broken windows from airborne projectiles. An approach to combining shading, privacy and protection that is gaining in popularity is the provision of adjustable louvers or shutters.

Access to light and air are among the most important considerations in housing design. It is estimated that urban dwellers spend approximately 90% of their time indoors, and this explains the importance of daylighting and natural ventilation to human well being. Unlike mechanical ventilation, which delivers outside air and exhausts stale, moist and contaminated indoor air through fans and ductwork, natural

ventilation relies on wind and buoyancy effects (stack pressures) to move air through openings typically located in windows and doors.

In this thesis the 11 passive strategies examined for each unit configuration are listed in Table 4.2. Envelope properties refers to the values stated in Table 4.1 for each climatic location.

For Base Case, the minimum requirements (MR) according to applicable building codes are assessed. In Case 1, for Toronto and Vancouver, a higher SHGC (Solar Heat Gain Coefficient) of 0.60 is tested, while a lower SHGC of 0.45 is tested for Adana. In Case 2, MIP (Movable Insulation Panels) are operated only during winter nights and modelled as Venetian blinds with a U-value of 0.5 W/m².K and zero airflow permeability. Case 3 considers a “better practice” (BP) enclosure, while 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/m².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 analyse 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 the 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 Case 9 and Case 10, respectively. Activation of these operable openings assumes ideal operation by occupants when indoor operative temperatures are 23 °C 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.

Table 4.2 : Passive measures applied in each of the 11 passive strategies examined.

	Envelope Properties			SHGC			MIP	Balcony				Shading Devices	Natural Ventilation	
	MR	BP	HP	Hi	Med	Low	0.5 W/m ² .K	Thermal		Overhang	Enclosed	Auto Sol-Air	5%	20%
								Break	Bridge					
Base Case	■			■										
Case 1	■			+		-								
Case 2	■			■			■							
Case 3		■			■									
Case 4			■			■								
Case 5			■			■			■					
Case 6			■			■		■		■				
Case 7			■			■		■			■			
Case 8			■			■						■		
Case 9			■			■						■		■
Case 10			■			■						■	■	
- Envelope properties correspond to the wall and glazing values listed in Table 1 for each city. - MR – minimum required by 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 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.														

4.4 Analysis of Thermal Autonomy Results

In this thesis the analysis of the parametric set of energy simulations focused on four cardinal directions separately. Even though, simulations are run for all three aspect ratio (2:1, 1:1, 1:2), the results are discussed through 2:1 unit. Because, the complete set of results show that the relative impact of parameters is same for all of them. Only, the larger the exterior surface and glazing area a unit has, the higher the energy consumption gets. Table 4.3 shows the difference between a 2:1 unit with 80% WWR (largest exterior wall and glazing area) and a 1:2 unit with 40% WWR

(smallest exterior wall and glazing area) for each orientation. Obviously, for the 1:2 unit with minimum glazing ratio, EUI ($\text{ekWh/m}^2\cdot\text{yr}$) is around 60% lower in all orientations. Thermally autonomous hours are also improving. On the other hand, daylighting analysis has not been considered but for 1:2 units less than 50% of floor area would receive acceptable daylighting.

For detailed analysis of a 2:1 unit, the first aspect examines the performance improvements after applying passive measures related to enclosure U-value and window-to-wall ratio. Second, additional passive strategies are tested on the best performing enclosure properties.

In this chapter, selected modelling results from south and north orientations are visualized to illustrate the thermal autonomy (TA) concept in each of the three climates. Then the results for all orientations are summarized and discussed in a table format. The detailed TA visualizations of west and east orientations can be seen in Appendix B. In the next chapter, the thermal autonomy metrics are compared to energy use intensity (EUI) for a greater understanding and validation of this time-based metric.

Table 4.3 : Comparison of 2:1 and 1:2 units with minimum envelope requirements.

	2x1	1x2
South	80% 2.5-0.45 0.278	40% 2.5-0.45 0.278
EUI (ekWh/m ² .yr)	41.3	16.0
TEDI (ekWh/m ² .yr)	12.1	6.6
Annual Heating (kWh)	773.2	422.3
Annual Cooling (kWh)	1863.8	597.9
Peak Heating (W)	2408.4	761.2
Peak Cooling (W)	2751.4	1066.2
% TA-Acceptable	20.2	28.4
% Active Heating	22.7	10.8
% Active Cooling	57.1	60.8
	2x1	1x2
West	80% 2.5-0.45 0.278	40% 2.5-0.45 0.278
EUI (ekWh/m ² .yr)	67.8	24.7
TEDI (ekWh/m ² .yr)	26.3	12.0
Annual Heating (kWh)	1677.1	763.4
Annual Cooling (kWh)	2649.5	813.9
Peak Heating (W)	2529.6	805.3
Peak Cooling (W)	5414.0	1692.1
% TA-Acceptable	10.1	13.6
% Active Heating	43.3	36.5
% Active Cooling	46.6	49.9
	2x1	1x2
North	80% 2.5-0.45 0.278	40% 2.5-0.45 0.278
EUI (ekWh/m ² .yr)	40.3	18.3
TEDI (ekWh/m ² .yr)	36.2	15.5
Annual Heating (kWh)	2307.5	986.5
Annual Cooling (kWh)	262.7	180.5
Peak Heating (W)	2650.8	895.6
Peak Cooling (W)	1284.3	722.6
% TA-Acceptable	19.7	22.7
% Active Heating	58.2	47.2
% Active Cooling	22.1	30.1
	2x1	1x2
East	80% 2.5-0.45 0.278	40% 2.5-0.45 0.278
EUI (ekWh/m ² .yr)	58.8	22.9
TEDI (ekWh/m ² .yr)	27.9	12.5
Annual Heating (kWh)	1778.4	797.6
Annual Cooling (kWh)	1970.1	665.8
Peak Heating (W)	2573.0	802.7
Peak Cooling (W)	4167.8	1479.9
% TA-Acceptable	11.1	17.4
% Active Heating	44.7	36.7
% Active Cooling	44.2	45.9

4.4.1 Toronto, ON, Canada

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

Figure 4.3 and Figure 4.4 visualize the thermal autonomy results for a south-facing unit with 80% WWR and 40% WWR, respectively. The high-performance 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 thermal autonomy 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 hours less overheating, it results in 150 hours less solar gains in winter.

Figure 4.5 illustrates the results corresponding to a north-facing unit with 80% WWR. The high-performance enclosure delivers the best thermal autonomy performance on an annual basis with 80% of the fraction of acceptable hours in a south-facing unit, compared to 46% of the fraction of acceptable hours in a north-facing unit.

Table 4.4 summarizes the thermal autonomy results for all orientations and window-to-wall ratios in Toronto.

In south; a higher thermal efficiency enclosure with 80% WWR improves cold weather TA from 30% to 15%, but worsens hot weather TA from 48% to 63%. Going from an 80% to 40% WWR has a significant effect on reducing hot hours, and considerable effect on increasing cold hours. But, for all enclosure properties, overall acceptable hours are similar. It is also important to note that, in a south-facing unit the highest efficient enclosure (case 4) doesn't make a positive difference compared to the average envelope case (case 3). This is because the highest U-Value causes heat traps, and increases too hot hours here. But, proper shading and natural ventilation strategies would solve that issue and utilize the benefit of high performance enclosure.

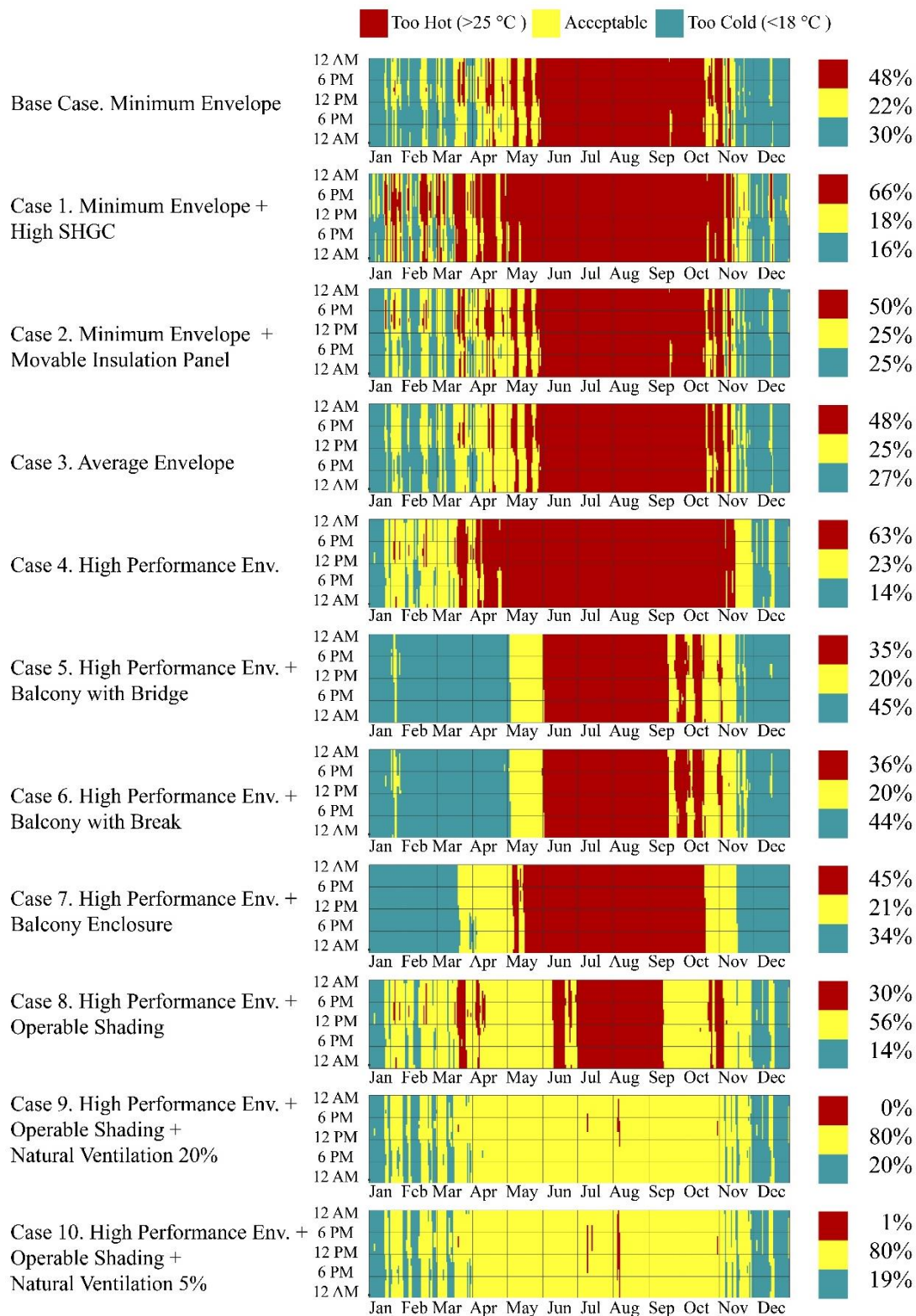


Figure 4.3 : Thermal autonomy performance of a south-facing unit with 80% WWR in Toronto, Canada.

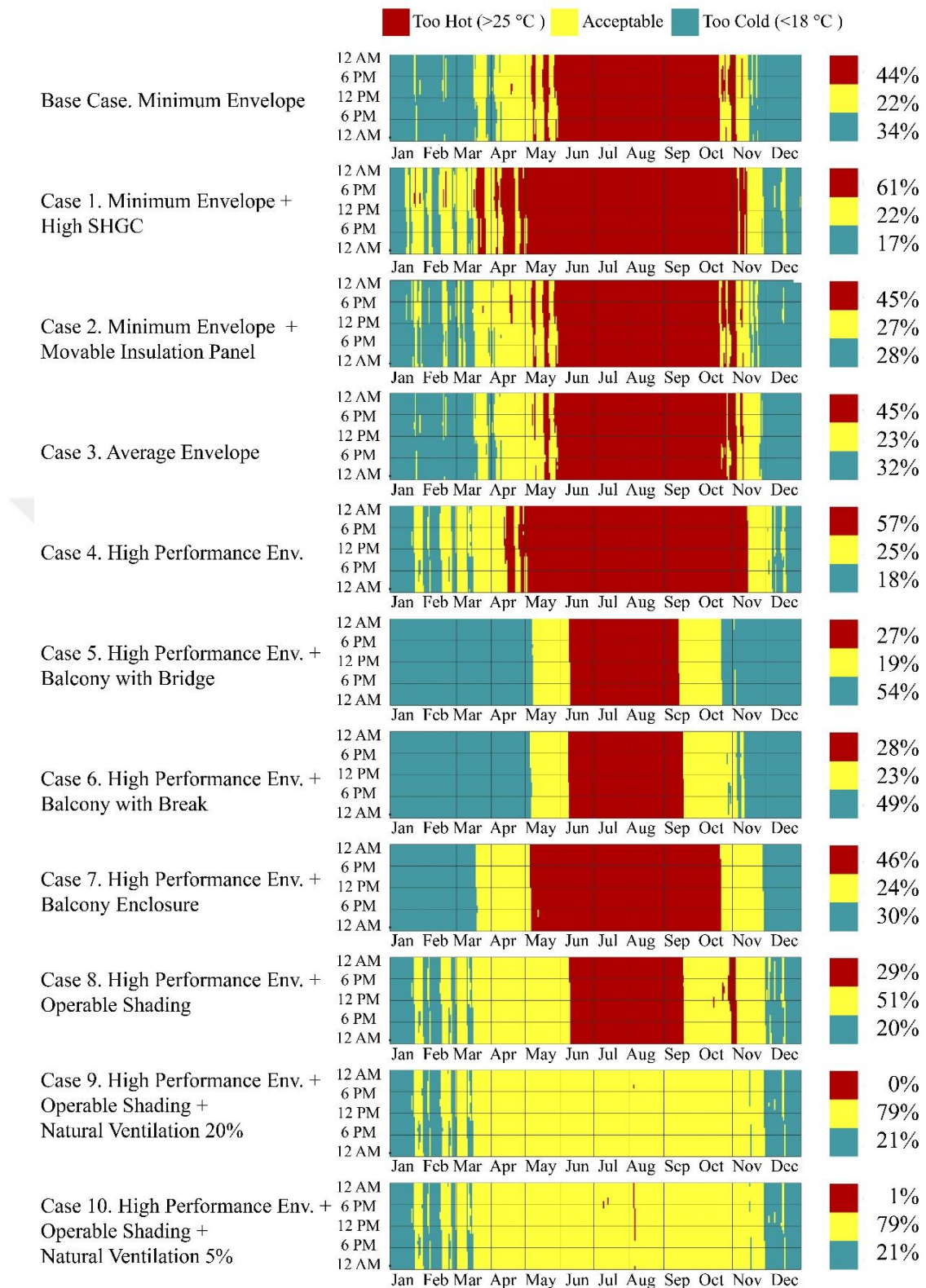


Figure 4.4 : Thermal autonomy performance of a south-facing unit with 40% WWR in Toronto, Canada.

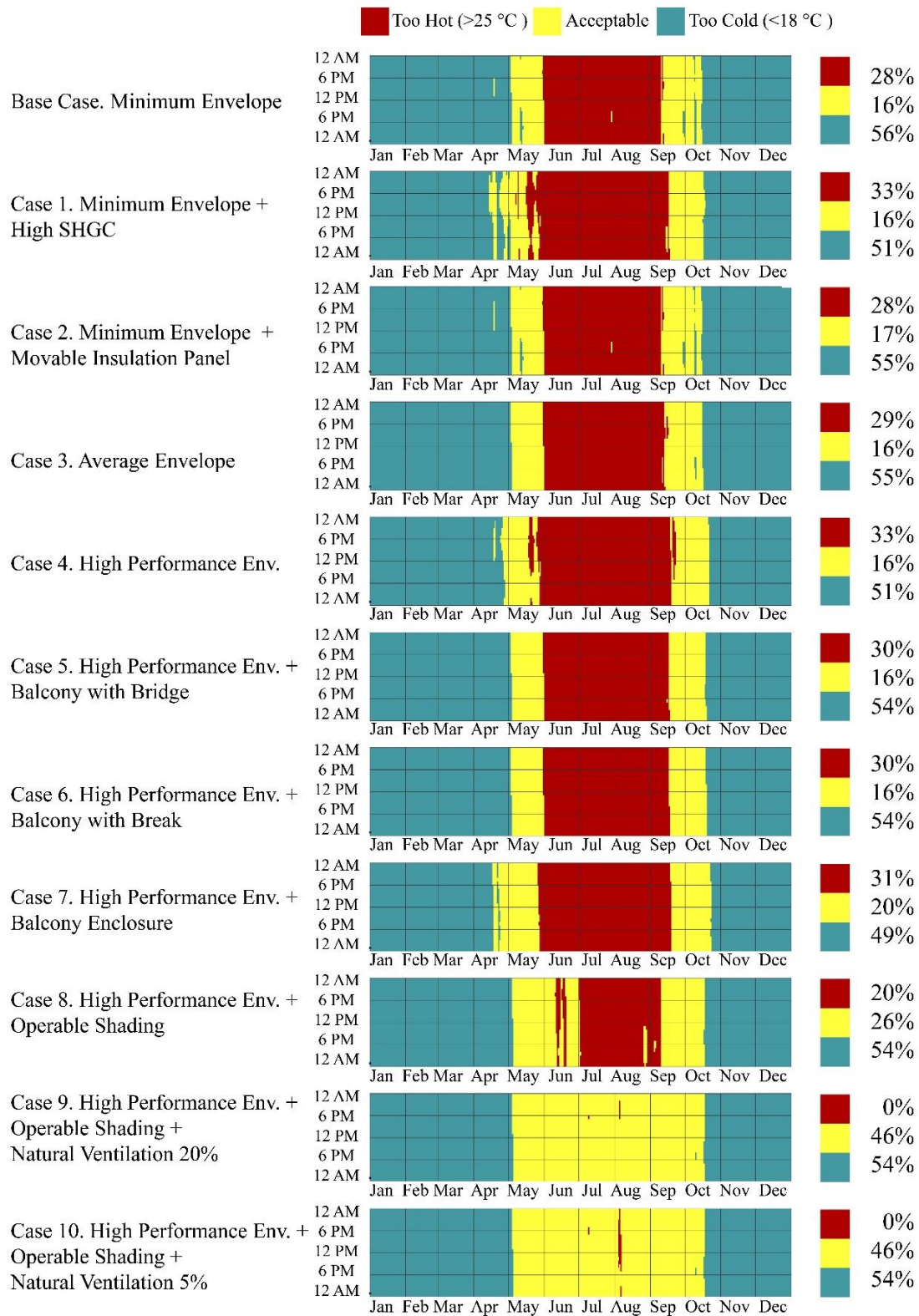


Figure 4.5 : Thermal autonomy performance of a north-facing unit with 80% WWR in Toronto, Canada.

Furthermore, results show that south-facing internal units with balcony overhangs (case 5) have less hot hours, but significantly more cold hours and overall acceptable hours are getting less compared to south-facing internal units with no balcony overhangs. Balconies that provide shading enhance hot weather thermal autonomy but block desirable solar gains in winter for south-facing units. When the fixed shading devices (balconies) exchanged for operable exterior shading devices (case 8), overall improvement is significant; thermal autonomy improves by two times. In case 6, the provision of thermal breaks improves overall acceptable hours if the WWR is 40%. Cooling energy demands were found to be higher for balconies with thermal breaks versus those without. The positive cooling effect of thermal bridging is small in absolute terms, but relatively high due to the thermally efficient enclosure. The analysis indicates that a significant proportion of the energy conservation benefits provided by balconies can be compromised by thermal bridging, hence thermal breaks at cantilevered balconies are necessary to preserve thermal integrity. Another strategy tested in south enclosed balcony with break (case 7) perform slightly better than a fully exposed balcony with break due to the former providing a buffer space but results less direct solar gains admitted to unit in cold days. Finally, in a south-facing unit, thermally efficient enclosure which has operable shading and provides natural ventilation delivers the best thermal autonomy performance on an annual basis.

Mostly, the impact of passive strategies at an 80% WWR unit are relatively similar to the results in a 40% WWR unit. Only, the provision of balcony overhang with bridge has higher negative impact, while enclosed balcony with break has less negative impact at an 80% WWR unit, because higher glazing area admits more direct heat gain in winter.

In north; a higher thermal efficiency enclosure with 80% WWR improves cold weather TA from 56% to 51%, but worsens hot weather TA from 28% to 33%. Going from an 80% to 40% WWR does not have as much effect as in South. But, it still causes more hot hours, and less cold hours.

Results show that, shading and natural ventilation strategies have not as significant impact as in south-facing unit as well, due to less cooling need. In a north-facing unit which has 80% WWR, enclosed balconies benefit more compared to 40%WWR because higher glazing area admits more direct heat gain in winter. The best

performing enclosure delivers the best thermal autonomy performance on an annual basis with a passive fraction of 80% in a south-facing unit, whereas a passive fraction of 47% is delivered in a north-facing unit.

In West; shading and natural ventilation strategies have as significant impact as in south-facing unit, due to high cooling need. Provision of breaks at balcony slabs has a slight impact in a west-facing unit with 40% WWR, and enclosed balcony with break does not perform better than a fully exposed balcony with break due to less direct solar gains admitted to unit and overheating of buffer space. Overall, the best performing enclosure delivers the best thermal autonomy performance on an annual basis with a passive fraction of 58% in a west-facing unit, which is quite significant.

In east; results show that, shading and natural ventilation strategies have as significant impact as in south and west facing units, due to high cooling need. Provision of breaks at balcony slabs has negative impact. In an east-facing unit with both 40% and 80% WWR, enclosed balcony with break perform better than a fully exposed balcony with break due to shielding effects that reduce heating loads and shading effects that reduce cooling loads. Overall, the best performing enclosure delivers the best thermal autonomy performance on an annual basis with a passive fraction of 60% in an east-facing unit, which is quite significant.

In summary, acceptable energy performance is achieved over a wide range of window-to-wall ratios (40% minimum for adequate daylighting to 80% practically fully glazed). South-facing units are largely passive. Based on the results for the four solar orientations, when lower WWR of 40% is used, enclosed balconies with thermal breaks do not perform better than open balconies with thermal breaks. However, when a higher WWR of 80% is used, enclosed balconies with thermal breaks perform better than open balconies with thermal breaks for the North and East orientations. Assuming the ideal operation of fully glazed and retractable balcony enclosures, these can provide enhanced comfort in the enclosed balcony buffer space while minimizing adverse impacts on energy performance.

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 thermal autonomy remains consistent – a high-performance enclosure with operable shading and natural ventilation delivers the best performance in the Toronto climate zone. Overall, the results show that a smart combination of

passive measures can permit higher window-to-wall ratios without significantly compromising thermal autonomy. Another interesting observation is that having 20% of the glazing area fitted with operable openings enhance warm weather thermal autonomy only marginally over the 5% operable openings case in Toronto.

Table 4.4 : Thermal autonomy results for all orientations and WWR in Toronto.

TORONTO	South		North		West		East	
	80	40	80	40	80	40	80	40
Base Case. Minimum Envelope	 48	 44	 28	 28	 44	 42	 47	 47
	 22	 22	 16	 17	 9	 12	 8	 6
	 30	 34	 56	 55	 47	 46	 45	 47
Case 1. Minimum Envelope + High SHGC	 66	 61	 33	 31	 50	 50	 52	 51
	 18	 22	 16	 17	 10	 9	 9	 12
	 16	 17	 51	 52	 40	 41	 39	 37
Case 2. Minimum Envelope + Movable Insulation Panel	 50	 45	 28	 28	 44	 43	 47	 47
	 25	 27	 17	 17	 10	 12	 10	 7
	 25	 28	 55	 55	 46	 45	 43	 46
Case 3. Average Envelope	 48	 45	 29	 30	 46	 44	 49	 47
	 25	 23	 16	 17	 8	 12	 6	 8
	 27	 32	 55	 54	 46	 44	 45	 45
Case 4. High Performance Envelope	 63	 57	 33	 32	 52	 49	 52	 50
	 23	 25	 16	 17	 9	 11	 12	 12
	 14	 18	 51	 51	 39	 40	 36	 38
Case 5. High Performance Env. + Balcony with Bridge	 35	 27	 30	 26	 38	 30	 45	 32
	 20	 19	 16	 19	 16	 17	 8	 17
	 45	 54	 54	 55	 46	 53	 47	 51
Case 6. High Performance Env. + Balcony with Break	 36	 28	 30	 28	 40	 33	 46	 37
	 20	 23	 16	 18	 15	 18	 8	 14
	 44	 49	 54	 53	 45	 49	 46	 49
Case 7. High Performance Env. + Balcony Enclosure	 45	 46	 31	 34	 42	 44	 45	 46
	 21	 24	 20	 19	 15	 16	 12	 15
	 34	 30	 49	 47	 43	 40	 43	 39
Case 8. High Performance Env. + Operable Shading	 30	 29	 20	 24	 31	 32	 43	 42
	 56	 51	 26	 23	 28	 26	 20	 19
	 14	 20	 54	 54	 41	 42	 37	 39
Case 9. High Perf. Env. + Op. Shading + Natural Vent. 20%	 0	 0	 0	 0	 1	 0	 0	 0
	 80	 79	 46	 47	 58	 57	 60	 60
	 20	 21	 54	 54	 41	 43	 40	 40
Case 10. High Perf. Env. + Op. Shading + Natural Vent. 5%	 1	 1	 0	 0	 2	 1	 1	 1
	 80	 79	 46	 47	 57	 56	 60	 59
	 19	 21	 54	 54	 41	 43	 39	 40
								
	 Too Hot (>25 °C)			 Acceptable		 Too Cold (>18 °C)		

4.4.2 Vancouver, BC, Canada

In the analysis of thermal autonomy, Figure 4.6 depicts results for a south-facing unit with 80% WWR. If the unit assumes only the minimum envelope requirements, it is thermally autonomous for 20% of the year, whereas the high-performance 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 thermal autonomy 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 to 13% and space cooling energy consumption by less than 1% (Ge et al. 2013). The smaller differences noted here, as compared to those reported in the literature, are due to assessing a significantly more thermally efficient enclosure. When the fixed shading devices (balconies) are exchanged for operable exterior shading devices, overall improvement is significant; thermal autonomous hours increase to 60% from 46%.

Figure 4.7 depicts results for a south-facing unit with 40% WWR. On the whole, a high performance envelope design which has 5% or 20% of the glazing area fitted with operable openings, and combined with operable shading and natural ventilation strategies, delivers the best thermal autonomy 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 façade in Vancouver.

Figure 4.8 presents the simulation results for a north-facing unit with 80% WWR. The difference between south and north-facing units is very obvious when thermal autonomy results are examined. The most high performance enclosure delivers the highest degree of thermal autonomy on an annual basis with the percentage acceptable hours of 82% in a south-facing unit (with 80% WWR), whereas a thermal autonomy of 44% is achieved in a north-facing unit. In summary, cold weather thermal autonomy for north-facing units is more challenging and an approach combining a high performance envelope and a shading device that incorporates thermal protection, such as enclosed balconies or moveable insulation panels, 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.

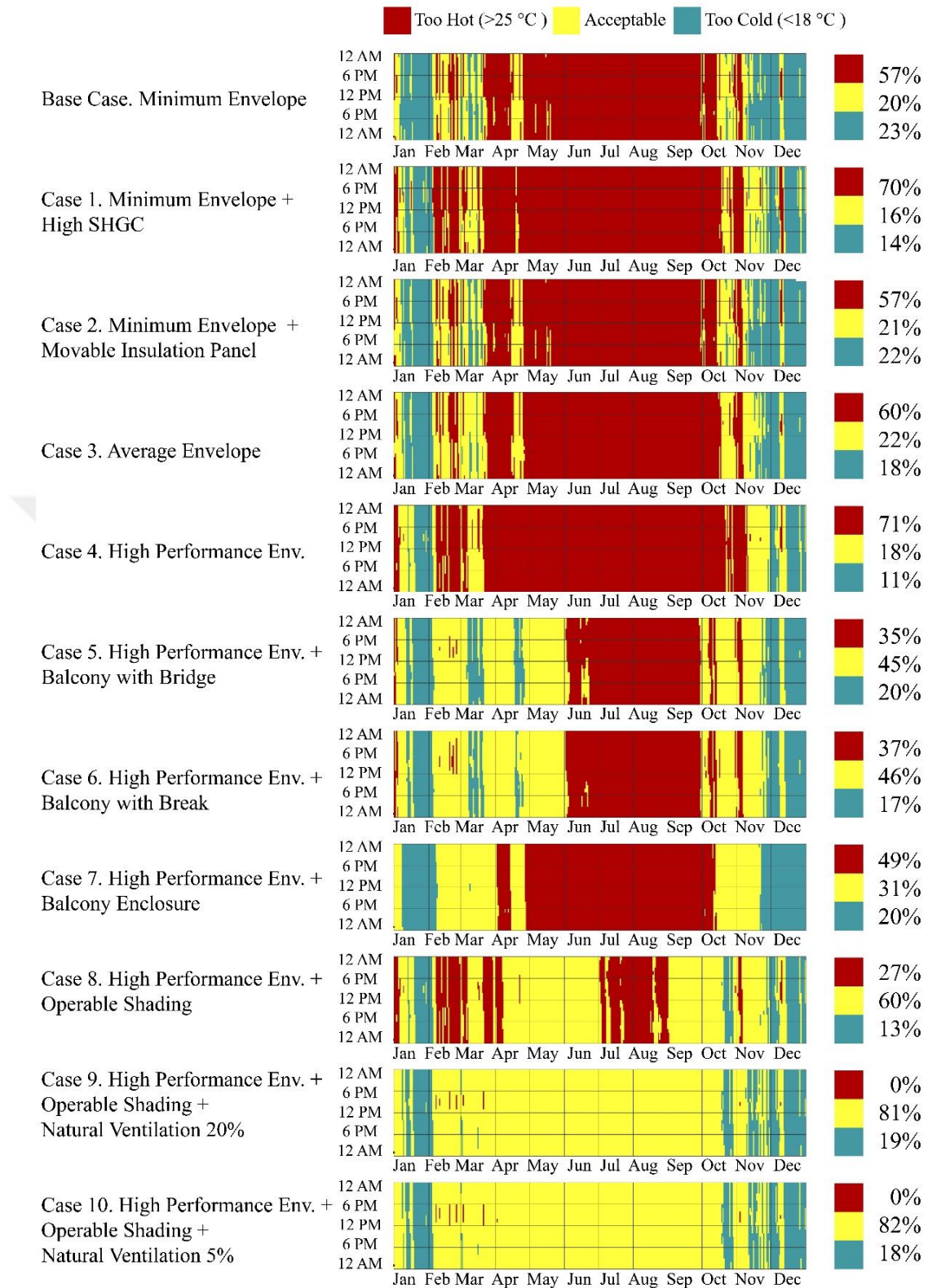


Figure 4.6 : Thermal autonomy performance of a south-facing unit with 80% WWR in Vancouver, Canada.

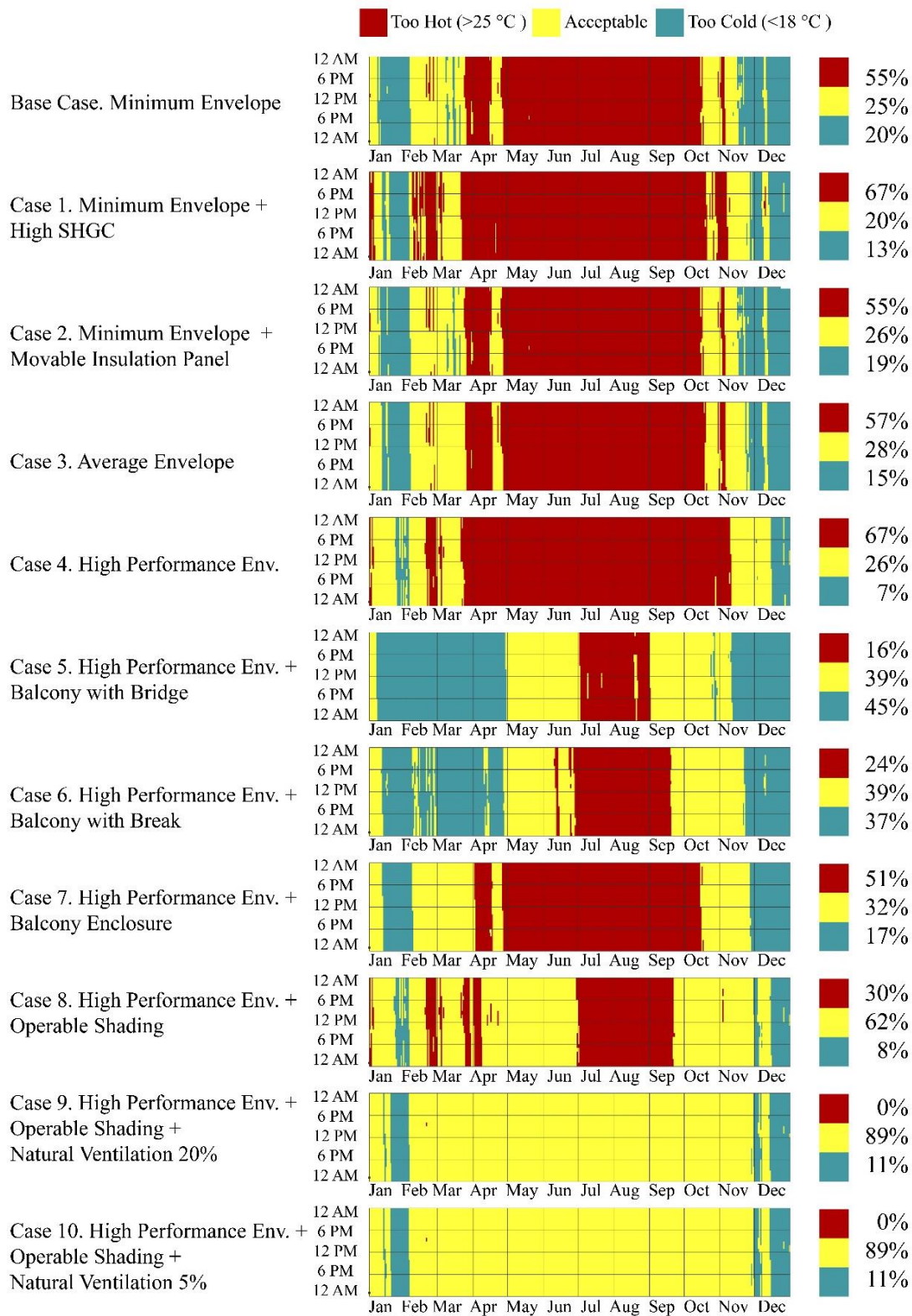


Figure 4.7 : Thermal autonomy performance of a south-facing unit with 40% WWR in Vancouver, Canada.

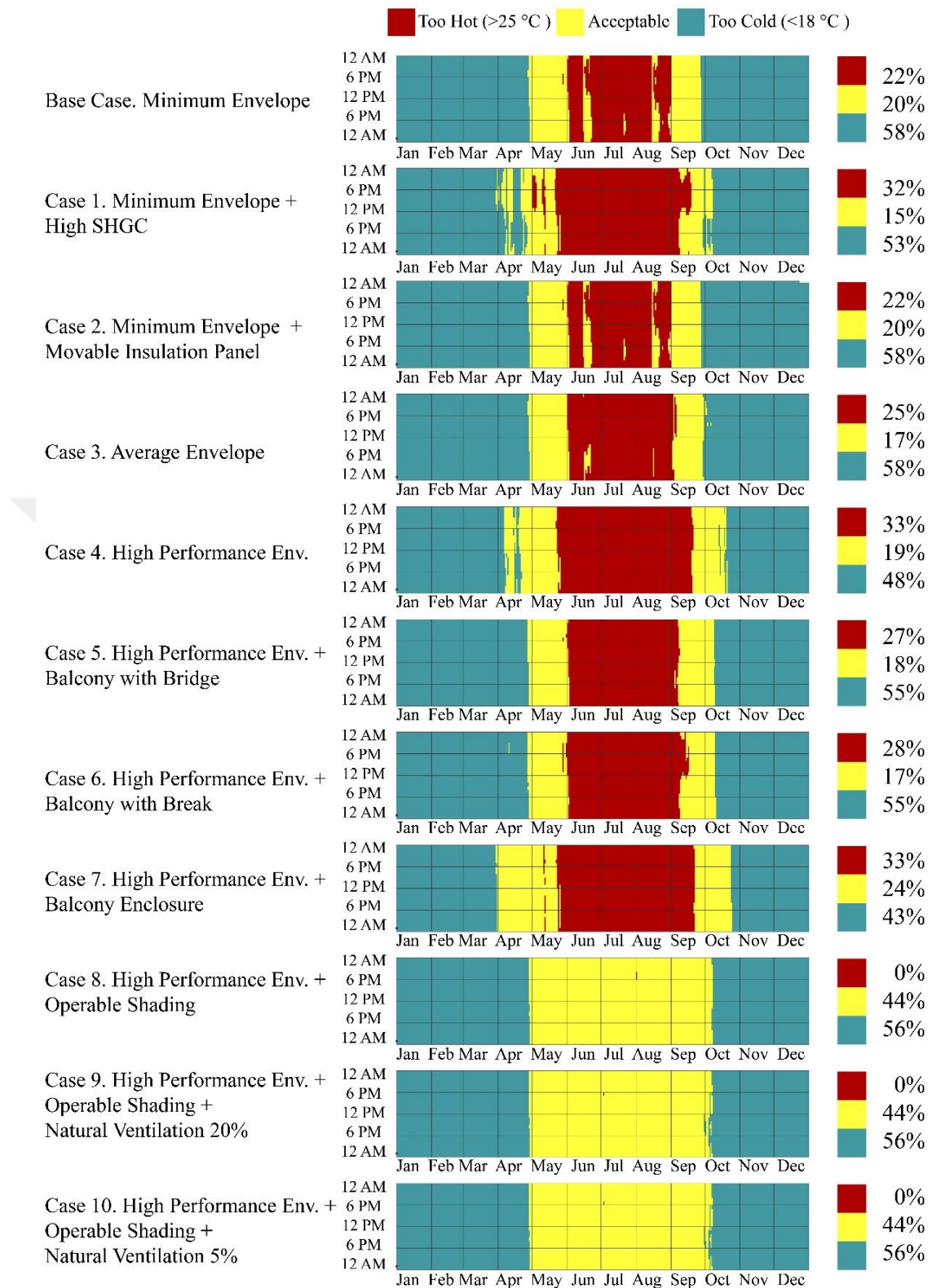


Figure 4.8 : Thermal autonomy performance of a north-facing unit with 80% WWR in Vancouver, Canada.

Table 4.5 summarizes the thermal autonomy results for all orientations and window-to-wall ratios in Vancouver.

In south; a higher thermal efficiency enclosure with 80% WWR improves cold weather TA from 23% to 11%, but worsens hot weather TA from 57% to 71%. Going from an 80% to 40% WWR has a significant effect on reducing hot hours, and considerable effect on increasing cold hours. But, for all enclosure properties, overall acceptable hours are similar. It is also important to note that, in a south-facing unit the highest efficient enclosure (case 4) makes a negative difference compared to the average envelope case (case 3). This is because the highest U-Value causes heat traps, and increases too hot hours here. But, proper shading and natural ventilation strategies would solve that issue and utilize the benefit of high performance enclosure.

Furthermore, results show that south-facing internal units with balcony overhangs (case 5) have more cold hours, but significantly less hot hours and overall acceptable hours are getting less compared to south-facing internal units with no balcony overhangs. Balconies that provide shading enhance hot weather thermal autonomy but block desirable solar gains in winter for south-facing units. When the fixed shading devices (balconies) exchanged for operable exterior shading devices (case 8), overall improvement is significant; thermal autonomy reaches to 60-62%. In case 6, the provision of thermal breaks improves overall acceptable hours if the WWR is 80%. Hot hours were found to be higher for balconies with thermal breaks versus those without, especially in a 40% unit. The positive cooling effect of thermal bridging is small in absolute terms, but relatively high due to the thermally efficient enclosure. The analysis indicates that a significant proportion of the energy conservation benefits provided by balconies can be compromised by thermal bridging, hence thermal breaks at cantilevered balconies are necessary to preserve thermal integrity. Another strategy tested in south enclosed balcony with break (case 7) does not perform better than a fully exposed balcony with break due to less direct solar gains admitted to unit and overheating of buffer space. Finally, in a south-facing unit, thermally efficient enclosure which has operable shading and provides natural ventilation delivers the best thermal autonomy performance on an annual basis.

Mostly, the impact of passive strategies at an 80% WWR unit are relatively similar to the results in a 40% WWR unit. Only, the provision of balcony overhang with bridge has higher negative impact, while enclosed balcony with break has less negative impact at an 80% WWR unit, because higher glazing area admits more direct heat gain in winter.

In north; a higher thermal efficiency enclosure with 80% WWR improves cold weather TA from 58% to 48%, but worsens hot weather TA from 22% to 33%. Going from an 80% to 40% WWR does not have as much effect as in South. But, it still causes more hot hours, and less cold hours.

Results show that, shading and natural ventilation strategies have not as significant impact as in south-facing unit as well, due to less cooling need. In a north-facing unit which has 80% WWR, enclosed balconies benefit more compared to 40%WWR because higher glazing area admits more direct heat gain in winter. The best performing enclosure delivers the best thermal autonomy performance on an annual basis with a passive fraction of 89% in a south-facing unit, where as a passive fraction of 50% is delivered in a north-facing unit.

In West; shading and natural ventilation strategies have as significant impact as in south-facing unit, due to high cooling need. Provision of breaks at balcony slabs has a slight impact in a west-facing unit with 80% WWR. Enclosed balcony with break performs better than a fully exposed balcony with break due to shielding effects that reduce heating loads and shading effects that reduce cooling loads for both WWR. Overall, the best performing enclosure delivers the best thermal autonomy performance on an annual basis with a passive fraction of 63% in a west-facing unit, which is quite significant.

In east; results show that, shading and natural ventilation strategies have as significant impact as in south and west facing units, due to high cooling need. Provision of breaks at balcony slabs has considerable impact if the unit has 40%WWR. In an east-facing unit benefits from an enclosed balcony with break only if it has 80% WWR. Overall, the best performing enclosure delivers the best thermal autonomy performance on an annual basis with a passive fraction of 63% in an east-facing unit, which is quite significant.

In summary, acceptable energy performance is achieved over a wide range of window-to-wall ratios (40% minimum for adequate daylighting to 80% practically fully glazed) as in Toronto. South-facing units are largely passive. The relationship between the passive measures producing the highest level of thermal autonomy remains consistent – a high-performance enclosure with operable shading and natural ventilation delivers the best performance in the Vancouver climate zone too. Overall, the results show that a smart combination of passive measures can permit higher window-to-wall ratios without significantly compromising thermal autonomy.



Table 4.5 : Thermal autonomy results for all orientations and WWR in Vancouver.

VANCOUVER	South				North				West				East					
	80		40		80		40		80		40		80		40			
Base Case. Minimum Envelope		57		55		22		23		47		44		44		43		
		20		25		20		20		10		14		11		14		
		23		20		58		57		43		42		45		43		
Case 1. Minimum Envelope + High SHGC		70		67		32		31		52		52		51		50		
		16		20		15		16		9		8		9		11		
		14		13		53		53		39		40		40		39		
Case 2. Minimum Envelope + Movable Insulation Panel		57		55		22		23		47		44		44		43		
		21		26		20		20		10		14		11		14		
		22		19		58		57		43		42		45		43		
Case 3. Average Envelope		60		57		25		26		48		46		45		44		
		22		28		17		19		10		13		13		15		
		18		15		58		55		42		41		42		41		
Case 4. High Performance Envelope		71		67		33		32		54		53		51		50		
		18		26		19		23		9		13		12		14		
		11		7		48		45		37		34		37		36		
Case 5. High Performance Env. + Balcony with Bridge		35		16		27		17		43		34		42		31		
		45		39		18		28		15		22		17		21		
		20		45		55		55		42		44		41		48		
Case 6. High Performance Env. + Balcony with Break		37		25		28		27		43		38		43		35		
		46		39		17		22		16		20		16		24		
		17		37		55		51		41		42		41		41		
Case 7. High Performance Env. + Balcony Enclosure		49		51		33		36		42		43		42		45		
		31		32		24		23		19		24		20		20		
		20		17		43		41		39		33		38		35		
Case 8. High Performance Env. + Operable Shading		27		30		0		11		33		34		23		33		
		60		62		44		39		27		29		36		30		
		13		8		56		50		40		37		41		37		
Case 9. High Performance Env. + Operable Shading + Natural Vent. 20%		0		0		0		0		0		0		0		0		
		81		89		44		50		60		63		58		63		
		19		11		56		50		40		37		42		37		
Case 10. High Performance Env. + Operable Shading + Natural Vent. 5%		0		0		0		0		0		0		0		0		
		82		89		44		50		60		63		58		63		
		18		11		56		50		40		37		42		37		
		Too Hot (>25 °C)					Acceptable					Too Cold (>18 °C)						

4.4.3 Adana, Turkey

In the analysis of thermal autonomy, Figure 4.9 and Figure 4.10 depict the results for a south-facing unit with 60% WWR and 30% 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 high-performance envelope properties cannot improve the performance by themselves since the internal and solar heat gains are further trapped. Having lower SHGC of glazing increases the percentage of acceptable hours to 2% in a unit with 60% WWR, while the reduced SHGC combined with 30% WWR reaches 5% of the fraction of acceptable hours.

Figure 4.11 summarizes the results corresponding to the south-facing unit with 60% WWR that is re-oriented to face north. Hot weather thermal autonomy for north-facing units is still challenging, but it also becomes important to consider strategies for improving cold weather thermal autonomy. Similar to the south-facing cases, when strategies are combined, the results show that a high-performance envelope design which has 20% of its glazing area fitted with operable openings, and combined with operable shading and natural ventilation strategies, delivers the best thermal autonomy for north-facing units at 63%.

Table 4.6 summarizes the thermal autonomy results for all orientations and window-to-wall ratios in Adana.

In south; high-performance envelope properties cannot improve the performance by themselves, additional passive strategies are needed. First, 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 area through a year. It is interesting to note that thermal bridging across the cantilevered balcony slab has a beneficial cooling effect in a unit with 30% WWR, but not in a unit with 60% WWR. This indicates that only modest solar heat gains can be effectively dissipated through thermal bridging. Interestingly, an operable shading strategy does not deliver thermal autonomy as effectively as a fully exposed balcony. This suggests large overhangs are better shading devices than exterior blinds, shades or louvers in south. Results show that a high-performance envelope design which has 20% of its glazing area fitted with operable openings, and combined with operable shading and natural ventilation strategies, delivers the best

thermal autonomy. For both the 60% and 30% WWR cases, acceptable hours of 71% on an annual basis are achieved using this combination of strategies.

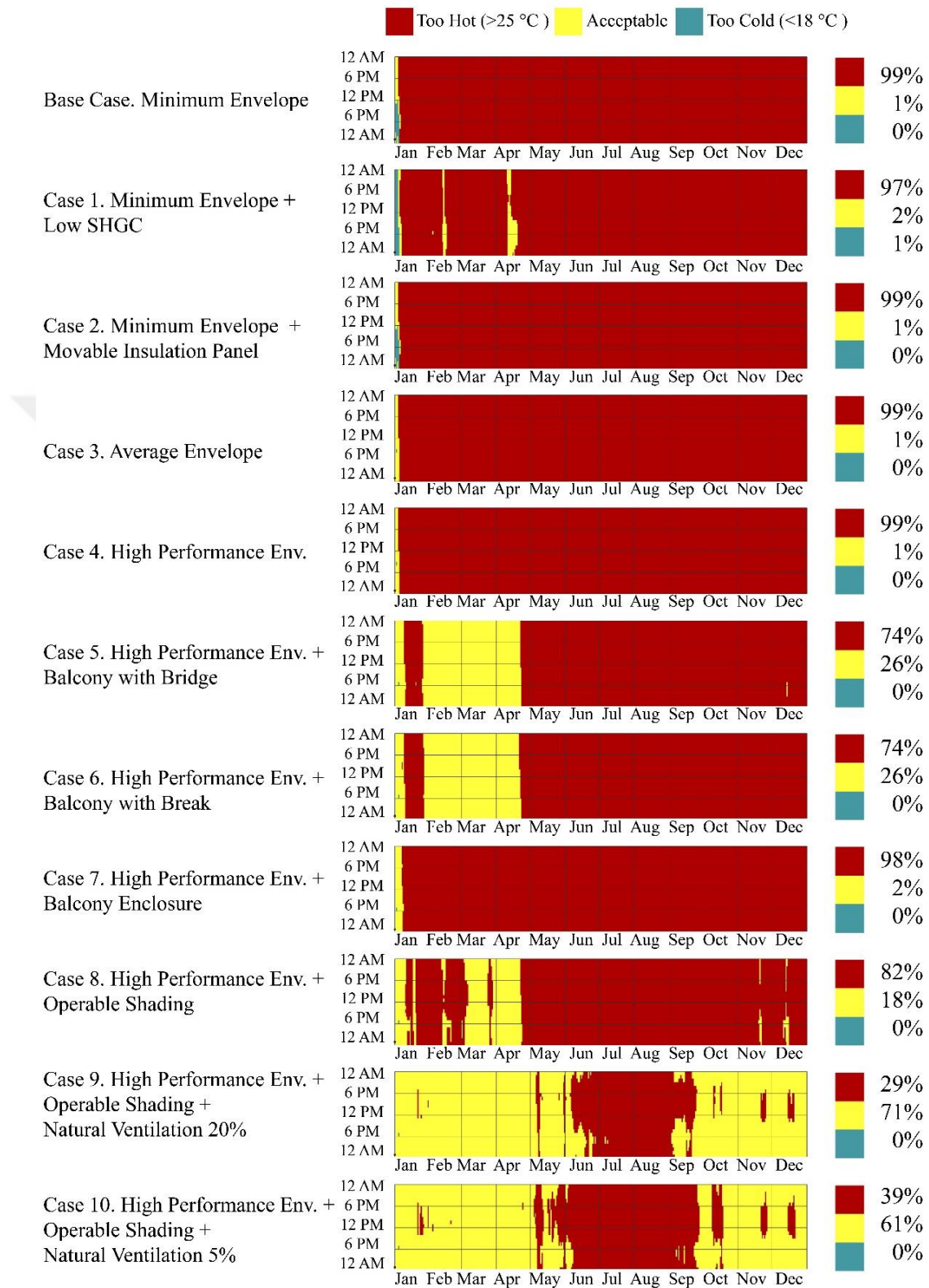


Figure 4.9 : Thermal autonomy performance of a south-facing unit with 60% WWR in Adana, Turkey.

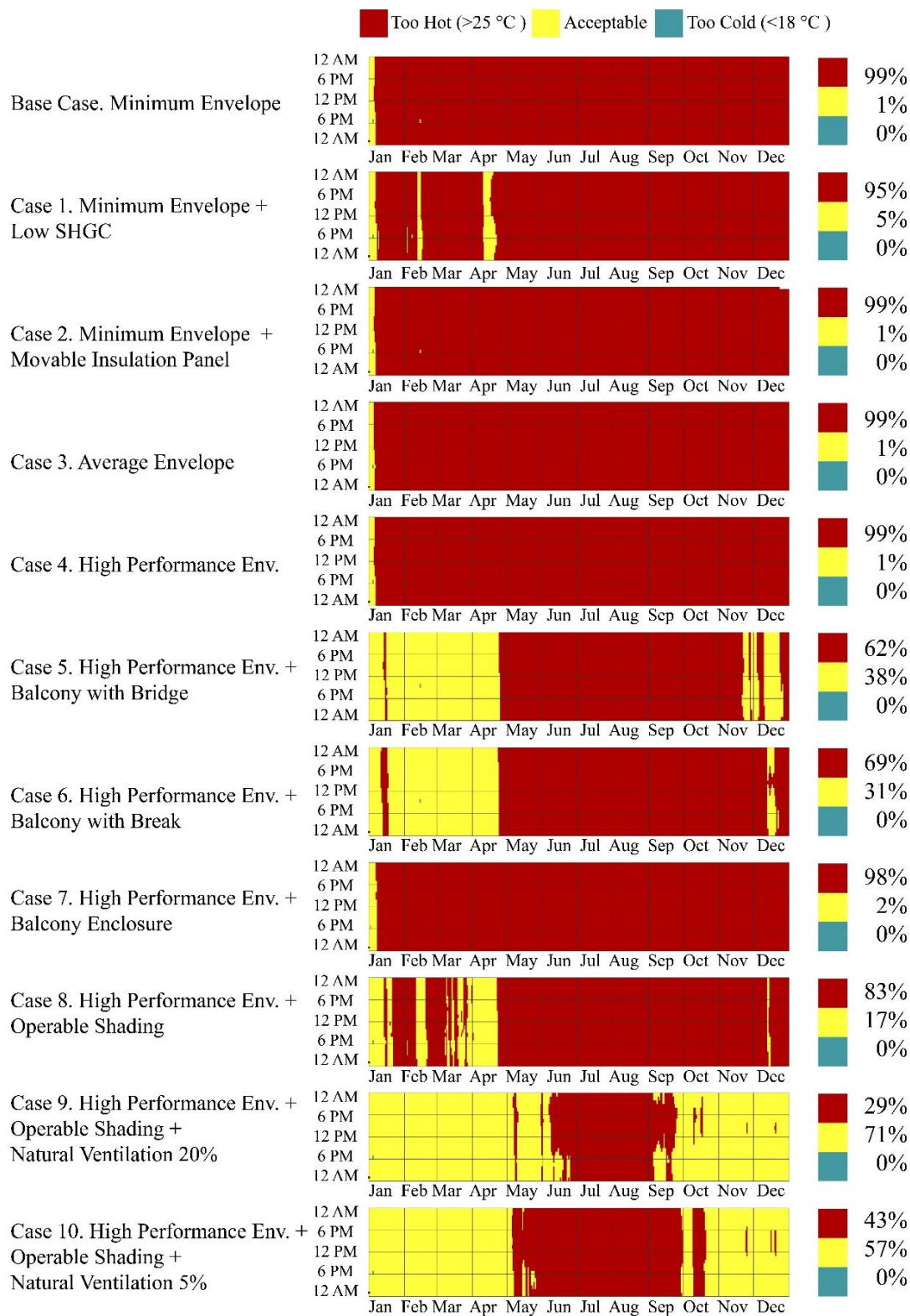


Figure 4.10 : Thermal autonomy performance of a south-facing unit with 30% WWR in Adana, Turkey.

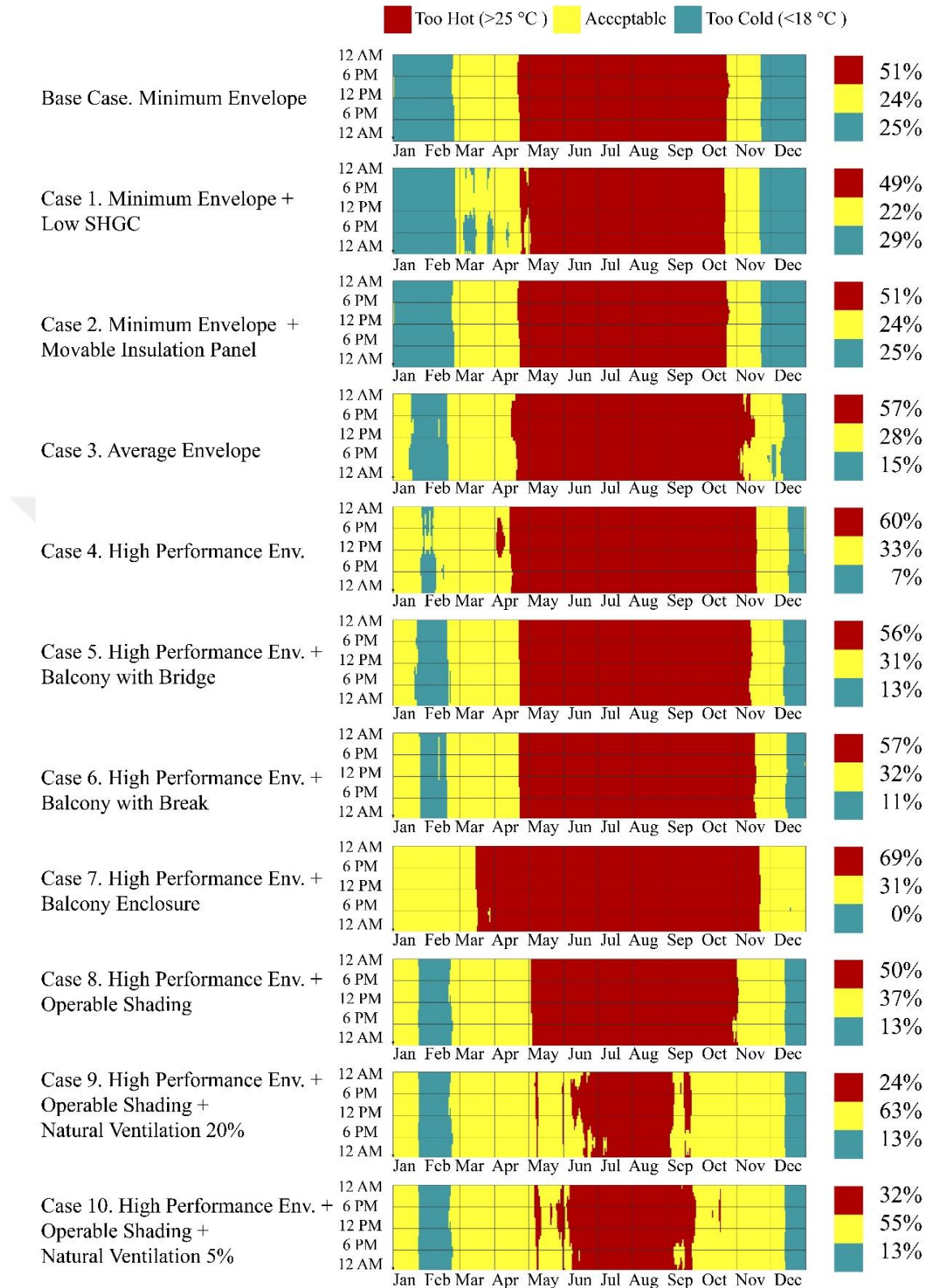


Figure 4.11 : Thermal autonomy performance of a north-facing unit with 60% WWR in Adana, Turkey.

In north; having lower SHGC of glazing decreases the percentage of acceptable hours to 22% from 24% in a unit with 60% WWR, while the reduced SHGC combined with 30% WWR increases the fraction of acceptable hours to 28% from 25%. Also, high-performance envelope properties improve the performance considerably in a north-facing unit. The provision of balcony slab does not have a beneficial impact in north because it worsens cold weather thermal autonomy. When the fixed shading devices (balconies) exchanged for operable exterior shading devices, overall improvement is considerable; thermal autonomy reaches to 37-38%. Finally, in a north-facing unit, thermally efficient enclosure which has operable shading and provides natural ventilation delivers the best thermal autonomy performance with 63% acceptable hours on an annual basis.

In west; even though the overall performance with minimum envelope case seems to be similar to north-facing unit, the percentage of hot hours is significantly higher and cold weather performance is better. Having lower SHGC of glazing in a unit with 60% decreases the overall performance due to causing more cold hours. The highest efficient enclosure makes a negative difference compared to the average and minimum envelope cases. This is because the highest U-Value causes heat traps, and increases too hot hours here. But, proper shading and natural ventilation strategies would solve that issue and utilize the benefit of high performance enclosure. Contrary to south, provision of balconies has a high shading effect for both WWR cases in west-facing units, but its impact is higher in a unit that has more glazing. Again contrary to south-facing unit, thermal break across the cantilevered balcony slab increases overall performance in a unit with 30% WWR, but decreases in a unit with 60% WWR. Having operable shading is preferable here, especially in a unit with 60% WWR, compared to fixed shading devices such as balcony overhangs. Overall, the best performing enclosure which has operable shading and provides natural ventilation delivers the best thermal autonomy performance on an annual basis with a passive fraction of 69% in a west-facing unit, which is quite significant.

In east; the reduced SHGC combined with 30% WWR increases the fraction of acceptable hours to 27% from 30% similar to north. The highest efficient enclosure makes a negative difference compared to the average and minimum envelope cases as in west-facing unit due to heat traps, and increased too hot hours. But, the provision of balcony slab is even more effective here. As in west, thermal bridging

across the cantilevered balcony slab has a beneficial cooling effect in a unit with 60% WWR, but a negative impact in a unit with 30% WWR. Having operable shading increases overall performance in a unit with 60% WWR, but decreases in a unit with 30% WWR. The best performing enclosure which has operable shading and provides natural ventilation delivers the best thermal autonomy performance on an annual basis with a passive fraction of 72% in an east-facing unit, which is quite significant in this particular hot climate.

In summary, acceptable energy performance is achieved over a wide range of window-to-wall ratios (30% minimum for adequate daylighting to 60% practically fully glazed) in Adana too. The best thermal autonomy performance in each orientation are quite similar to each other.

Furthermore, an enclosed balcony cannot be a reasonable option due to overheating from solar gains to the enclosed buffer space in any orientation. Cold weather thermal autonomy can be improved through the provision of enclosed balconies in north, but in order not to compromise hot weather thermal autonomy, the balcony enclosure must be designed to open completely, effectively behaving like an unenclosed balcony as required.

Based on the analysis of thermal autonomy for Adana, Turkey climate zone, it is observed that the thermal and optical characteristics of the envelope, including the window-to-wall ratio, 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 thermal autonomy. It is also important to note that, contrary to the Toronto and Vancouver climatic locations, in a cooling dominated climate like Adana, Turkey, 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.

Table 4.6 : Thermal autonomy results for all orientations and WWR in Adana.

ADANA	South		North		West		East	
	60	30	60	30	60	30	60	30
Base Case. Minimum Envelope	99	99	51	51	75	73	74	73
	1	1	24	25	24	27	25	27
	0	0	25	24	1	0	1	0
Case 1. Minimum Envelope + Low SHGC	97	95	49	47	70	65	70	66
	2	5	22	28	20	27	25	30
	1	0	29	25	10	8	5	4
Case 2. Minimum Envelope + Movable Insulation Panel	99	99	51	51	75	73	74	73
	1	1	24	25	24	27	25	27
	0	0	25	24	1	0	1	0
Case 3. Average Envelope	99	99	57	54	81	76	84	75
	1	1	28	31	19	24	16	25
	0	0	15	15	0	0	0	0
Case 4. High Performance Envelope	99	99	60	57	83	78	91	76
	1	1	33	34	17	22	9	24
	0	0	7	9	0	0	0	0
Case 5. High Performance Env. + Balcony with Bridge	74	62	56	51	62	58	66	57
	26	38	31	32	37	36	34	40
	0	0	13	17	1	6	0	3
Case 6. High Performance Env. + Balcony with Break	74	69	57	56	68	59	71	58
	26	31	32	33	32	41	29	42
	0	0	11	11	0	0	0	0
Case 7. High Performance Env. + Balcony Enclosure	98	98	69	72	81	84	81	91
	2	2	31	28	19	16	19	9
	0	0	0	0	0	0	0	0
Case 8. High Performance Env. + Operable Shading	82	83	50	50	64	59	66	64
	18	17	37	38	36	41	34	36
	0	0	13	12	0	0	0	0
Case 9. High Performance Env. + Operable Shading + Natural Vent. 20%	29	29	24	25	31	31	28	29
	71	71	63	63	69	69	72	71
	0	0	13	12	0	0	0	0
Case 10. High Performance Env. + Operable Shading + Natural Vent. 5%	39	43	32	37	41	44	37	42
	61	57	55	51	59	56	63	58
	0	0	13	12	0	0	0	0
	Too Hot (>25 °C)			Acceptable		Too Cold (>18 °C)		

4.5 Analysis of Passive Survivability Results

Passive survivability, 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 shall also be resilient (O'Brien and Bennet, 2016). In the current study, passive survivability 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 applying the current metrics with weather files that incorporate the impacts of climate change on extreme weather events.

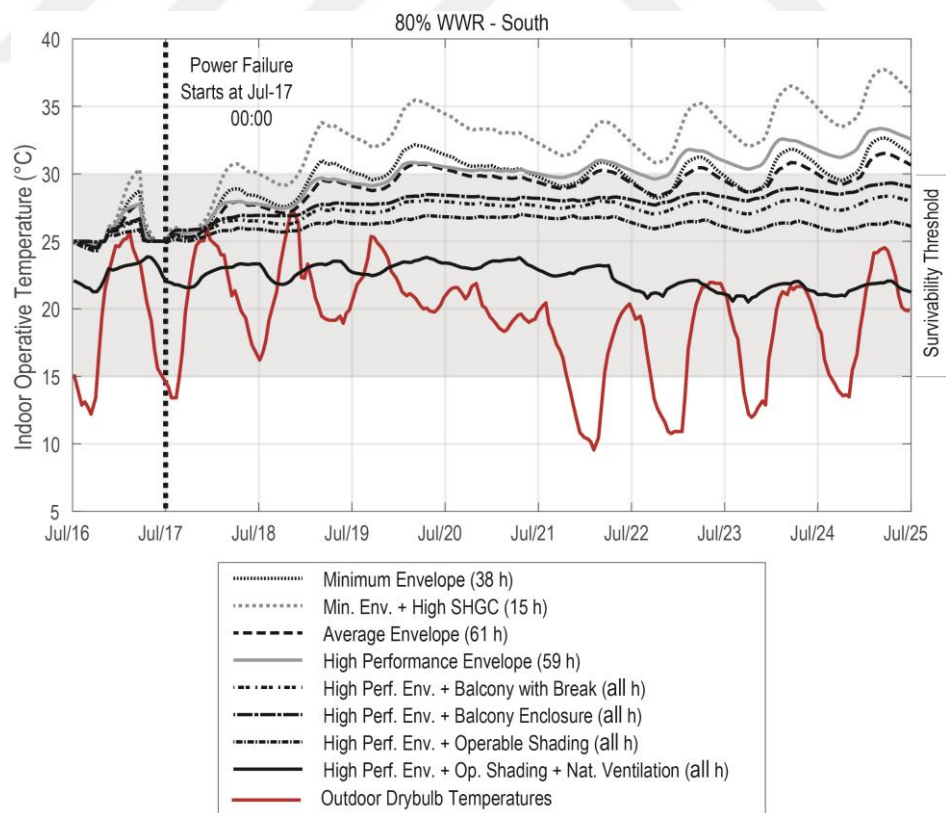


Figure 4.12 : Passive survivability performance for a south-facing unit with 80% WWR under summer conditions.

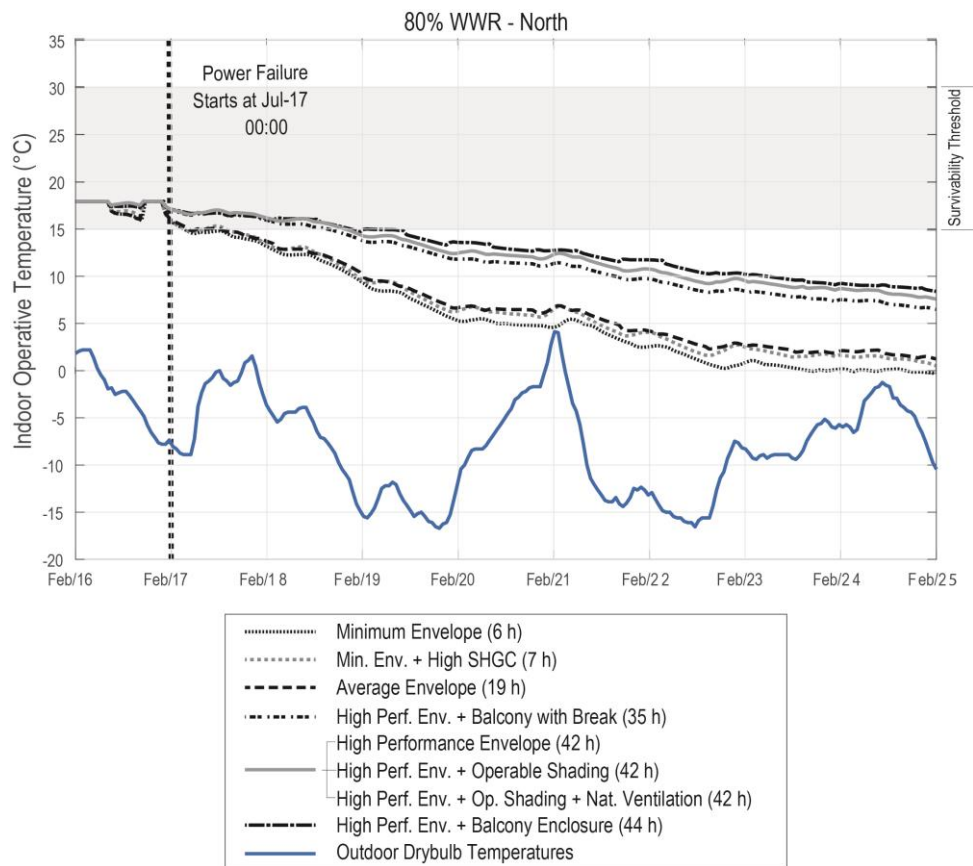


Figure 4.13 : Passive survivability performance for a north-facing unit with 80% WWR under winter conditions.

Passive survivability performance is depicted in Figure 4.12 and Figure 4.13, which depict south and north-facing units with 80% WWR in Toronto, respectively. The indoor operative temperatures (y-axis) are tracked for eight days (x-axis) after the power failure in summer and winter, and indicate that designs with high thermal autonomy also tend to have better passive survivability. Selected passive survivability results are also presented in a table format to illustrate the use of the approach and summarize the results for each climatic location. The visualizations of passive survivability for all orientations can be seen in Appendix C.

In Table 4.7, 4.8 and 4.9 the time-based results are presented 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 in

Toronto, Vancouver and Adana, respectively. The table 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 to thermal autonomy analysis, wider temperature thresholds are chosen for passive survivability analysis, since “survivability” suggests marginally acceptable temperatures.

Table 4.7 : Passive survivability performance in Toronto associated with various passive measures corresponding to cases described in Tables 1 & 2.

			Base Case 80% or 60 % WWR Minimum Envelope	Case 4 80% or 60 % WWR High Perf. Envelope	Case 9 80% or 60 % WWR High Perf. Envelope & Operable Shading & Natural Ventilation	Base Case 40% or 30 % WWR Minimum Envelope	Case 4 40% or 30% WWR High Perf. Envelope	Case 9 40% or 30 % WWR High Perf. Envelope & Operable Shading & Natural Ventilation
Toronto	South Unit_2x1	PS- Winter (hours)	118	all	221	124	all	all
		PS- Summer (hours)	38	59	all	183	182	all
	North Unit_2x1	PS- Winter (hours)	6	42	42	30	64	64
		PS- Summer (hours)	65	187	all	469	423	all
	West Unit_2x1	PS- Winter (hours)	27	56	56	46	103	103
		PS- Summer (hours)	40	61	all	137	138	all
	East Unit_2x1	PS- Winter (hours)	8	77	77	48	115	115
		PS- Summer (hours)	9	10	all	37	63	all
- Passive survivability indicated as consecutive hours before habitability thresholds are exceeded. 80% and 40% WWRs are highest and lowest ranges respectively for Toronto.								

Most cases with high-performance enclosures fare relatively well and maintain tolerable conditions for two to three days or longer. An important consideration is the required duration of passive survivability 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 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 are able to 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 high-performance envelope cases are able to maintain comfortable temperatures in all orientations except north. Enclosure properties (U-Value and SHGC of glazing), followed by window-to-wall ratio, are the most effective parameters to achieve passive survivability in a north-facing unit.

Table 4.8 : Passive survivability performance in Vancouver associated with various passive measures corresponding to cases described in Tables 1 & 2.

			Base Case 80% or 60 % WWR Minimum Envelope	Case 4 80% or 60 % WWR High Perf. Envelope	Case 9 80% or 60 % WWR High Perf. Envelope & Operable Shading & Natural Ventilation	Base Case 40% or 30 % WWR Minimum Envelope	Case 4 40% or 30% WWR High Perf. Envelope	Case 9 40% or 30 % WWR High Perf. Envelope & Operable Shading & Natural Ventilation
Vancouver	South Unit_2x1	PS- Winter (hours)	316	all	all	all	all	all
		PS- Summer (hours)	135	134	all	183	182	all
	North Unit_2x1	PS- Winter (hours)	49	164	164	99	370	370
		PS- Summer (hours)	all	328	all	all	all	all
	West Unit_2x1	PS- Winter (hours)	100	all	all	274	all	all
		PS- Summer (hours)	20	92	all	115	137	all
	East Unit_2x1	PS- Winter (hours)	92	all	all	199	all	all
		PS- Summer (hours)	10	128	all	152	152	all
- Passive survivability indicated as consecutive hours before habitability thresholds are exceeded. 80% and 40% WWRs are highest and lowest ranges respectively for Vancouver.								

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 passive survivability metric may only be useful for summertime power failures. Enhanced

hot climate passive survivability may also benefit from the deployment of passive cooling techniques presented in the literature (Santamouris et al., 2007).

Table 4.9 : Passive survivability performance in Adana associated with various passive measures corresponding to cases described in Tables 1 & 2.

			Base Case 80% or 60 % WWR Minimum Envelope	Case 4 80% or 60 % WWR High Perf. Envelope	Case 9 80% or 60 % WWR High Perf. Envelope & Operable Shading & Natural Ventilation	Base Case 40% or 30 % WWR Minimum Envelope	Case 4 40% or 30% WWR High Perf. Envelope	Case 9 40% or 30 % WWR High Perf. Envelope & Operable Shading & Natural Ventilation
Adana	South Unit_2x1	PS- Winter (hours)	all	all	all	all	all	all
		PS- Summer (hours)	37	59	424	40	86	all
	North Unit_2x1	PS- Winter (hours)	all	all	all	all	all	all
		PS- Summer (hours)	38	60	all	65	103	all
	West Unit_2x1	PS- Winter (hours)	all	all	all	all	all	all
		PS- Summer (hours)	16	17	113	19	41	163
	East Unit_2x1	PS- Winter (hours)	all	all	all	all	all	all
		PS- Summer (hours)	10	16	211	31	34	187
- Passive survivability indicated as consecutive hours before habitability thresholds are exceeded. 60% and 30% WWRs are highest and lowest ranges respectively for Adana.								

4.6 The Survey Results

The majority of the 65 participants were architects (40%) and engineers (40%), followed by 9% technicians. 11% participants identified themselves as belonging to other professions, such as educator, contractor, consultant, planner and sustainability specialist. Participants were asked about their years of experience in a building performance related profession. The majority of participants (75%) had more than 5 years of experience. The vast majority of participants work in Canada (94%), with the rest working in the United States and Panama. 50% of the participants encounter building energy performance related work every day, while 20% encounter it a few

times a week. When asked how they visualize building performance simulation data, participants mostly stated that they use graphs or charts created in spreadsheets for visualizing building performance data mostly, while features in building simulation tools, graphs or charts created in programming tools and manual methods to overlay data on 2D and 3D drawings are the other frequently-used methods.

With regards to how familiar the participants are with the most common metrics and units in current practice (Figure 4.14), most of them are extremely familiar (35%) or very familiar (26%) and these are the participants who find those metrics and units useful for making decisions about mechanical system. These participants mostly tended to give the same response for passive design decisions. But 12% of the participants, who find these metrics and units very useful or somewhat useful for making decisions about mechanical systems, think they are less or not very useful for making decisions about passive design decisions. The majority of participants agree (43%) or strongly agree (14 %) that these metrics are aimed at engineers more than architects, while 30% of participants are neutral about this statement. Understandably, the architects who have more than 20 years of experience in that field, mostly disagree with the statement while the rest of the architects mainly agree, or neutral at least. Interestingly, there is only one engineer participant who disagrees, while 70% of engineers agree these metrics are aimed at engineers more than architects.

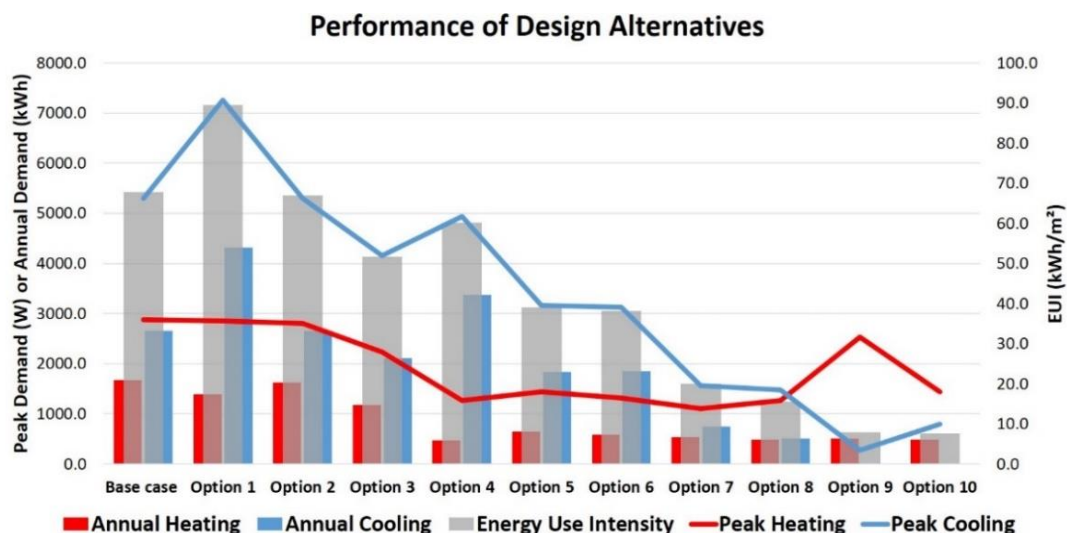


Figure 4.14 : A common use of energy metrics.

In the next category, 90% of participants responded correctly to the question of which design option causes the most overheating in the demonstrative thermal autonomy graph (Figure 4.15) and 8% of participant stated they did not understand the graph.

Examining the questions of to what extent participants agree or disagree with the statements regarding the use of TA graphs for facilitating decision making during the early design stage (Figure 4.16), the vast majority (77%) of participants agree or strongly agree that the graphs indicate how a building design might perform independently from mechanical systems, while 68% of participants also agree or strongly agree that they give an idea when or if mechanical systems can be turned off.

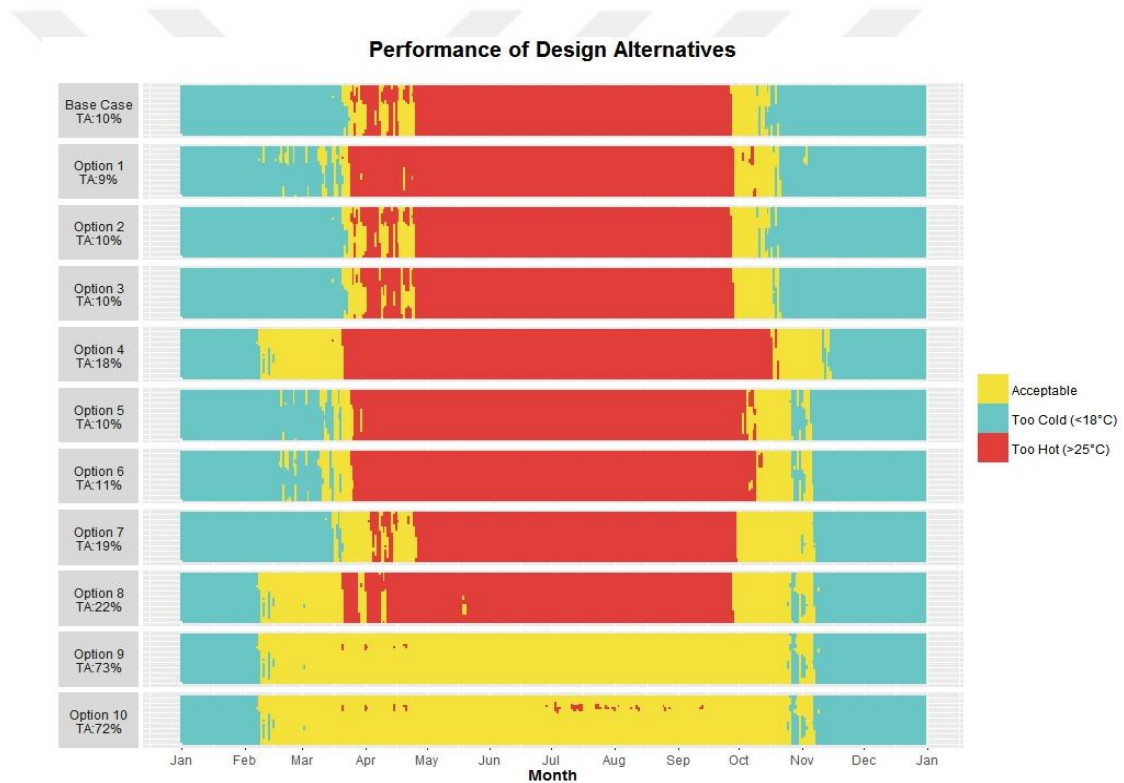


Figure 4.15 : Former Visualization of Thermal Autonomy.

Similarly, the majority (71%) of participants agree that the graphs show seasonal patterns and are useful for facilitating passive system design decision making. On the other hand, 48% of participants agree or strongly agree that the graphs predict occupant comfort, and 49% of participants agree the graphs are intuitive, while 25% and 17% of participants, respectively, disagree or strongly disagree with that statement. Much fewer participants (28%) agree or strongly agree that TA have

temporal resolution that is sufficient to understand the building's energy performance while 28% of participants disagree or strongly disagree with that statement, and rest of them are neutral. This reveals the need for more comprehensive study to correlate thermal autonomy to enhanced energy performance. Overall, the vast majority (74%) of participants responded that if TA graphs were available to them at the early stages of their building designs, they would use them.

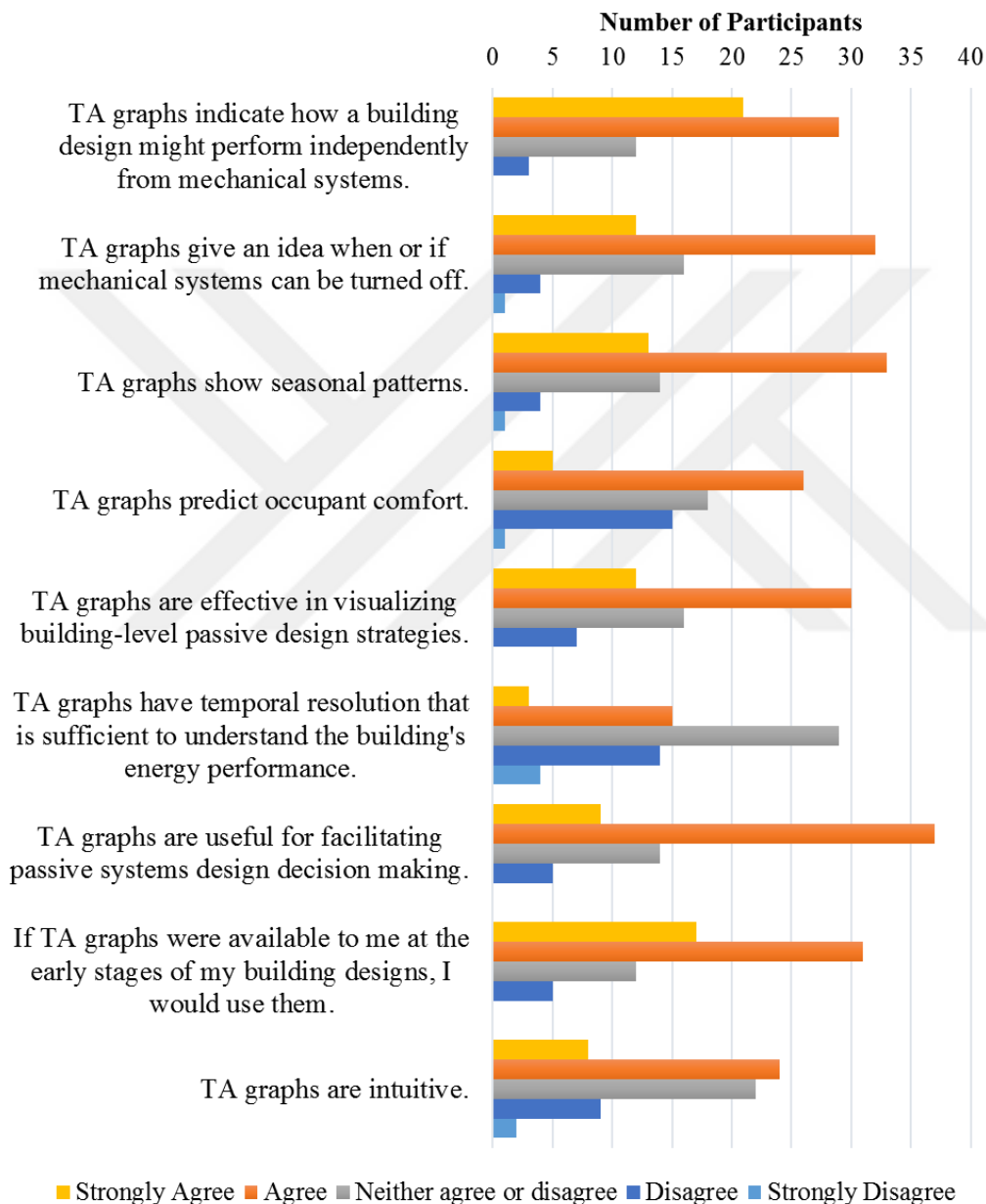


Figure 4.16 : Statements regarding the use of TA graphs for facilitating decision making during early design stage.

The most common comments and suggestions to improve TA graphs include adding a label for the Y- axis (time of day), larger text and fonts, providing better resolution

of day/night data, and adding % of hours for each of the three categories (too hot, too cold, and acceptable) because they think decisions require numbers to confirm. There are participants who think incorporating indoor relative humidity into this concept is fundamental. Their comments suggest that indoor moisture (e.g., RH) will have a big effect on occupant comfort and most passive (ventilation) systems will not provide the same level of control that mechanical systems would.

In the PS category of questions, 86% of participants responded correctly to the question of which passive strategy provides the longest period of tolerable interior temperatures after a power failure in the PS graph (Figure 4.17) and 8% of participant stated they didn't understand the graph.

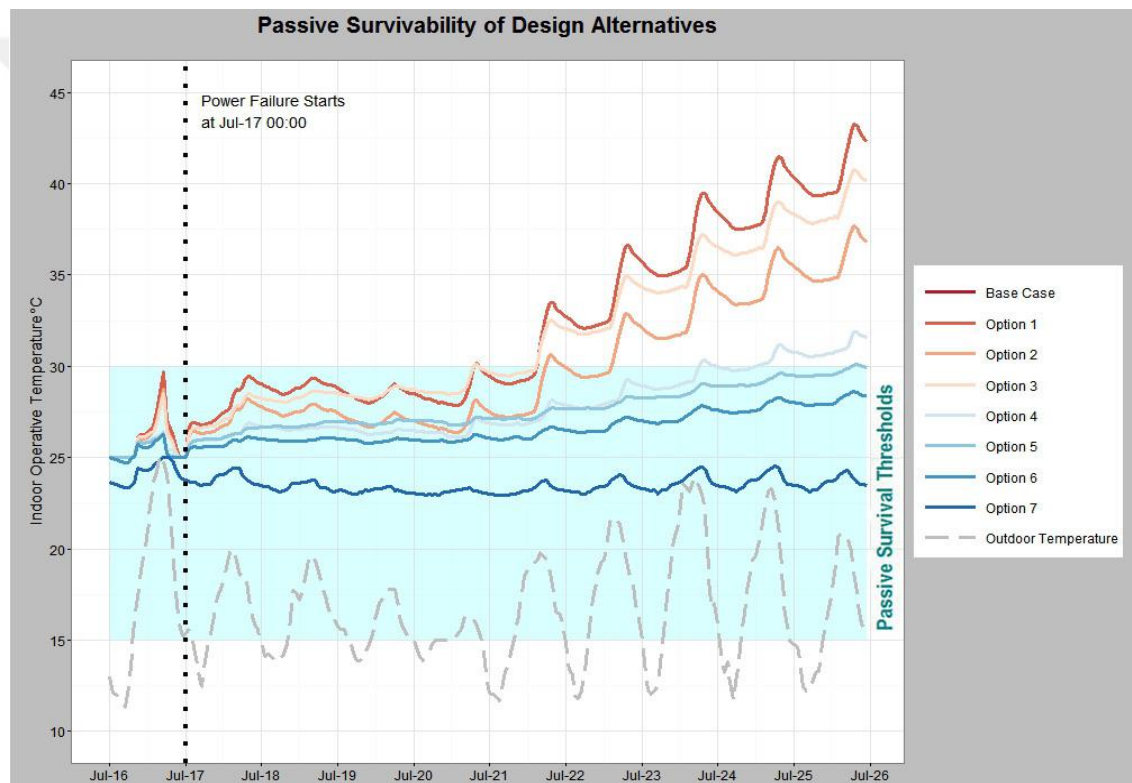


Figure 4.17 : Former Visualization of Passive Survivability.

In the questions of to what extent participants agree or disagree with the statements regarding the use of PS graphs for facilitating decision making during the early design stage (Figure 4.18), the vast majority (83%) of participants agree or strongly agree that the graphs indicate how a building design might perform independently from mechanical systems, while 77% of participants also agree or strongly agree that they are useful for improving resilient design decision. Similarly, the majority (71%) of participants agree the graphs are effective in visualizing building-level design

strategies. On the other hand, 57% of participants are agree or strongly agree that the graphs predict occupant comfort, and 63% of participants agree the graphs are intuitive, while 15% and 9% of participants, respectively, are disagree or strongly disagree with that statement. Unlike the responds to TA graph, the cast majority (69%) of participant agree or strongly agree that PS have temporal resolution that is sufficient to understand the indoor comfort conditions during extended power system failures. Overall, the vast majority (74%) of participants responded that if PS graphs were available to them at the early stages of their building designs, they would use them. The most common comments and suggestions to improve PS graphs include having larger text and more distinct colors, and adding number of hours in the passive survival zone for each category. There are participants who think that depending on climate, humidity and fresh air are important considerations as well.

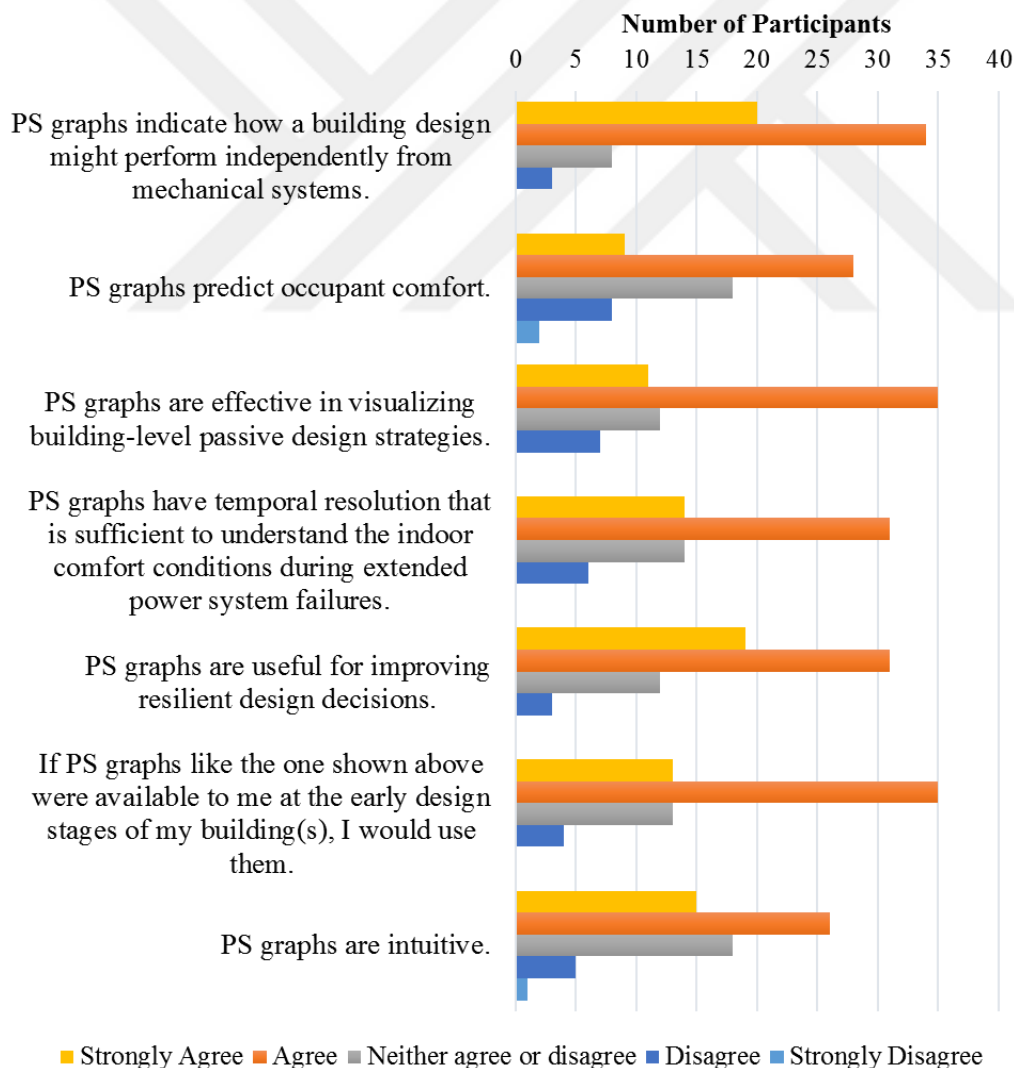


Figure 4.18 : Statements regarding the use of PS graphs for facilitating early decision making.

In the last category of questions, the majority (65%) of participants responded both conventional metrics (kW, kWh and kWh/m².year) and Thermal Autonomy and Passive Survivability are useful for the design of passive systems while 14% of participants think TA and PS are most useful metrics and 11% of participants indicate they don't know enough about energy performance modelling to decide. Most of the participants are interested in having the visualization of time-based metrics for thermal comfort (88%) and daylighting (80%) in further studies (Figure 4.19).

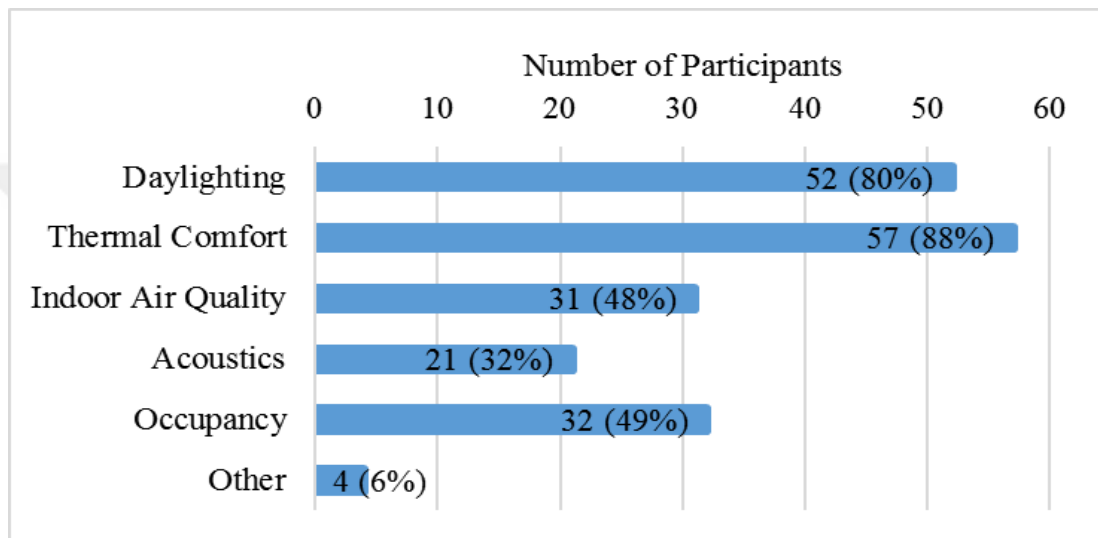


Figure 4.19 : Other performance parameters for possible future studies.



5. DISCUSSION OF THE APPROACH AND RESULTS

This thesis has investigated how the visualization of time-based metrics can be used to effectively inform the early stages of design so that enhanced energy performance, comfort and resilience may be achieved in buildings. In this chapter, the proposed approach is discussed through examining the correlation of Thermal Autonomy with EUI, and based on the survey results.

5.1 Discussion on the Correlation of Thermal Autonomy with EUI

One question this study attempts to answer is the significance of TA as an indicator of energy performance. In a former paper by Ozkan et al. (Ozkan, 2017), the relationship between EUI (energy use intensity) and TA (fraction of year) was explored. In another former paper by Ozkan et al. a more extensive analysis and discussion are presented by comparing TA versus EUI for Toronto (Figure 5.1), Vancouver (Figure 5.2) and Adana (Figure 5.3). (Figure 5.3).

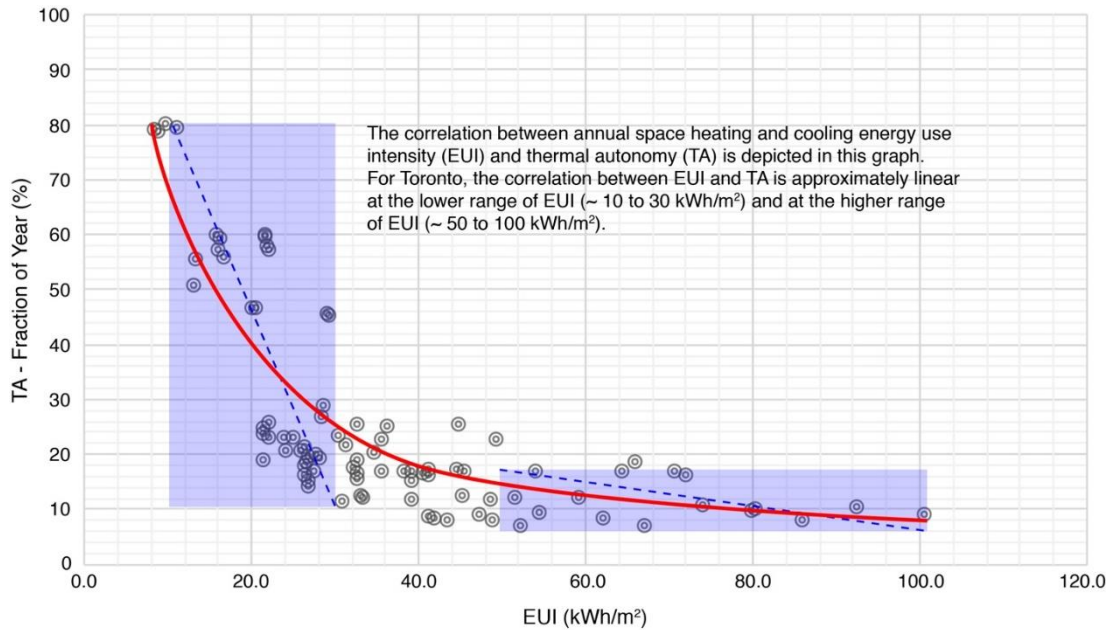


Figure 5.1 : Correlation of space heating and cooling energy use intensity (EUI) with thermal autonomy (TA) for all cases assessed in Toronto, Canada.

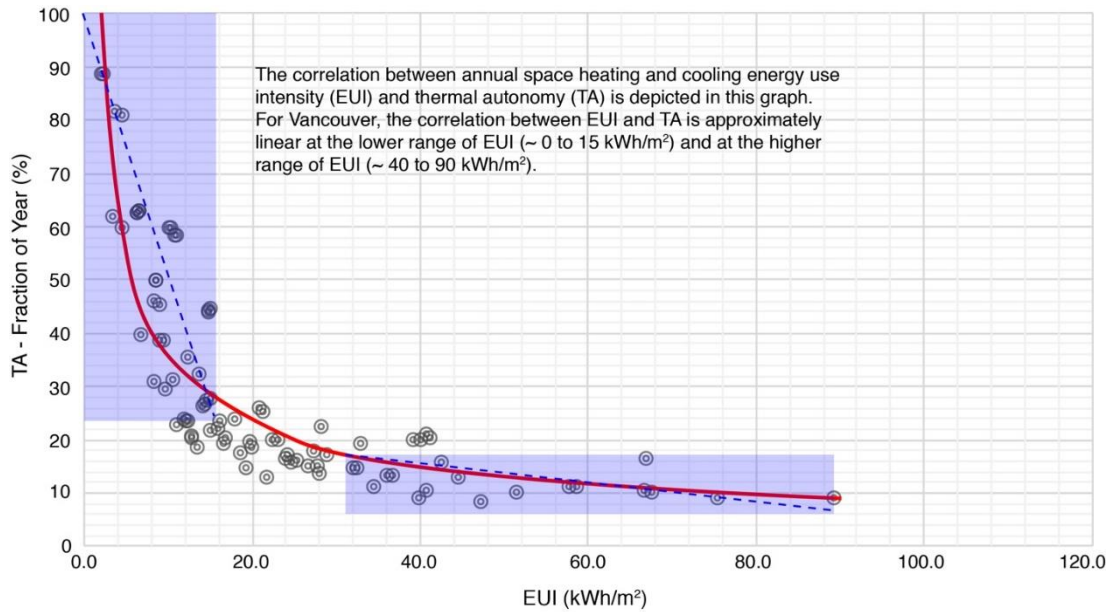


Figure 5.2 : Correlation of space heating and cooling energy use intensity (EUI) with thermal autonomy (TA) for all cases assessed in Vancouver, Canada.

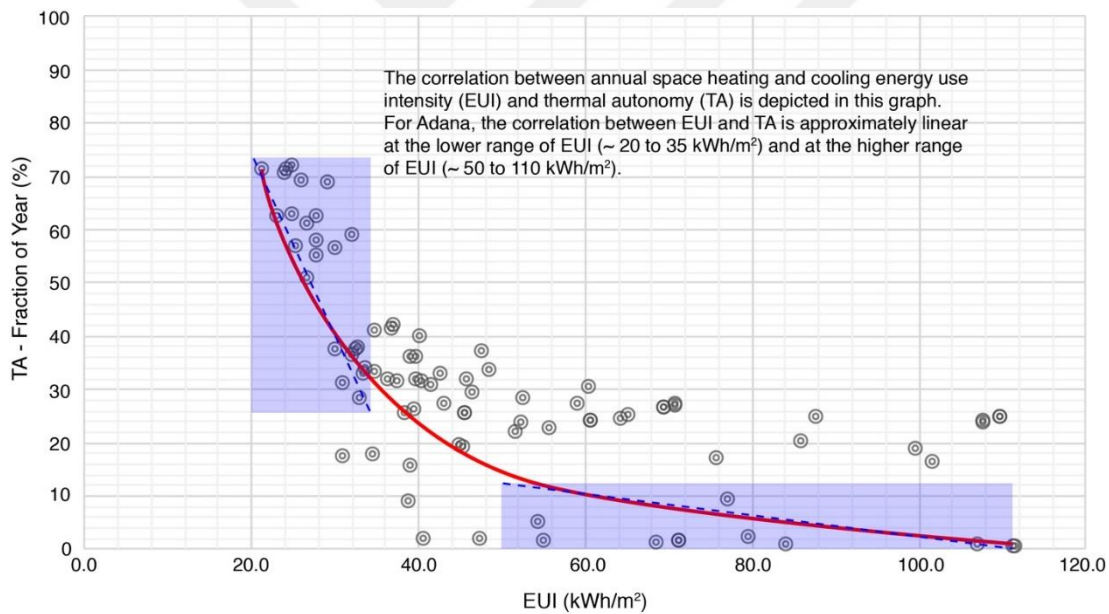


Figure 5.3 : Correlation of space heating and cooling energy use intensity (EUI) with thermal autonomy (TA) for all cases assessed in Adana, Turkey.

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 thermal autonomy 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 thermal autonomy and energy use intensity becomes stronger.

Future research should investigate the relationship between thermal autonomy and the space heating and cooling energy use intensity 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 thermal autonomy is strongly correlated to space heating and cooling energy use intensity, and in general the higher the TA, the lower the EUI.

5.2 Discussion of the Approach Based on the Survey Results

As a summary of the survey results, the responses of the participants indicated the following:

1. TA graphs are intuitive and indicate how a building design might perform passively, independent from mechanical systems. TA graphs have temporal resolution that is sufficient to understand the building's energy performance.
2. 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.
3. PS graphs are also useful for improving resilient design decisions because they display information at a human scale with familiar metrics: time and temperature.
4. 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 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 that are provided by strategies involving building form, orientation, fabric and fenestration.

6. CONCLUSIONS

This thesis has investigated how the visualization of time-based metrics can be used to effectively inform the early stages of design so that enhanced energy performance, comfort and 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 thermal autonomy and passive survivability 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 aim 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 highlighted are related to new areas identified during the study that need further attention, while the last three point to existing and ongoing research gaps:

1. 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.
2. 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.

3. 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?
4. A consistent methodology 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.
5. 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.
6. The accurate modelling of natural ventilation is critical for hot weather thermal autonomy 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 thesis demonstrates that the assessment of passive strategies, by visualizing thermal autonomy and passive survivability metrics, is a promising means of guiding the early stages of design for low energy buildings.

6.1 Practical Application of This Study

The research presented in this thesis was motivated by two factors: the unacceptable comfort and resilience exhibited in modern, highly glazed multi-unit residential buildings; and how the conventional deployment of building performance simulation has failed to substantially improve these critical aspects of buildings, 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 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.

Research conducted for apartment building typologies indicates 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. But the work presented herein only represents a promising methodology 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.

6.2 Limitations

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 to suggest the results are applicable beyond the types of multi-unit residential buildings 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 thermal autonomy 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 (Colet et

al., 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 and Levin, 2015).

Third, measures of passive survivability 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 optimally operate their buildings during extreme events by purely passive means. Moreover, occupants' ability to actively improve their comfort 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 compartmentalize 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.

6.3 Future Research

This comprehensive study has raised questions for possible future research. First, future research should investigate the relationship between thermal autonomy and the space heating and cooling energy use intensity for an entire building, not just individual suites. Second, future research should focus on applying the current metrics with weather files that incorporate the impacts of climate change on extreme weather event, and how to create a commonly accepted weather data file that can be

used to consistently evaluate extreme cases for PS analysis. Third research question may be how to create benchmarks to consistently apply time-based metrics in the early design stage. Finally, another research should look into how to define comfort thresholds that are appropriate for the analysis of only passive measures in naturally ventilated buildings.





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APPENDICES

APPENDIX A : Online survey questions.

APPENDIX B : Thermal Autnomy Graphs.

APPENDIX C : Passive Survivability Graphs.

APPENDIX D : MATLAB code for PS graphs.





APPENDIX A : Online survey questions

Online Survey can be found in this link: <https://goo.gl/forms/y5tICxTagqVaKO5x2> and the questions are provided below.

The Effectiveness of Visualizing Time-based Metrics of Thermal Autonomy and Passive Survivability in Building Performance Simulations

This short survey is led by Aylin Ozkan, Research Associate, University of Toronto as part of her PhD thesis. If you have any questions or concerns about the survey, please feel free to contact Aylin Ozkan (aylin.ozkan@daniels.utoronto.ca).

The survey should take 5-10 minutes, and your responses are completely anonymous. Your information will not be shared with anyone.

Your participation in this research study is voluntary. If you decide to participate in this research survey, you may withdraw at any time prior to submitting the survey. As the study is anonymous, you will not be able to withdraw once you have clicked “submit”, unless you provide your email address.

All research data will be encrypted. The company running the online survey is Google based in the USA. The data will be deleted once the survey is complete, after when, it will be accessible by only the researchers (Aylin Ozkan, Dr. Ted Kesik, University of Toronto, and Dr. William O'Brien, Carleton University). Once the project is completed, all research data will be kept for five years and potentially used for other research projects on the same topic. At the end of five years, all research data will be deleted.

If you would be willing to be contacted for clarification about your answers, please provide your email address.

By clicking “I agree to participate”, you consent to participate in the research study as described above.

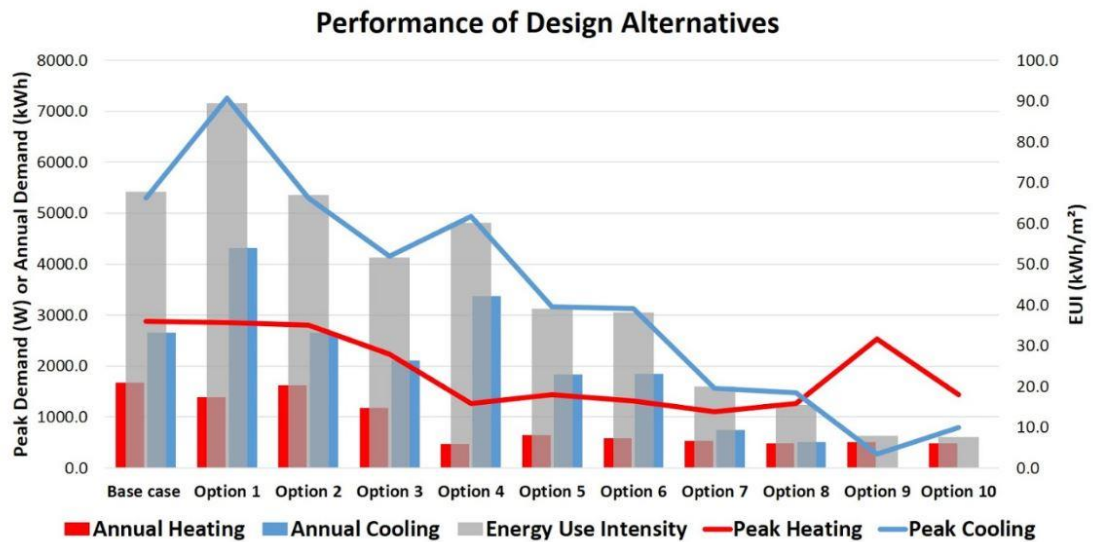
- ☐ I agree to participate
- ☐ I do not agree to participate

Background Information

- 1) Which of the following best describes your profession?
 - a. Architect
 - b. Engineer
 - c. Technician / Technologist
 - d. Other
- 2) Where are you working/studying primarily?
 - a. Canada
 - b. USA
 - c. Europe
 - d. Other
- 3) How many years of experience do you have with a building energy performance-related profession?
 - a. 0
 - b. 1-5
 - c. 5-10
 - d. 10-20
 - e. More than 20
- 4) How often do you come across a building energy performance related work in your practice?
 - a. Everyday
 - b. A few times a week
 - c. A few times a month
 - d. A few times a year
 - e. Never
- 5) What methods, if any, do you currently use for visualizing building performance?
 - a. Features in building simulation tools
 - b. Graphs or charts created in spreadsheets
 - c. Graphs or charts created in programming tools
 - d. Manual methods to overlay data on 2D and 3D drawings.
 - e. Each time I am using a different method.
 - f. Other

Knowledge of Common Energy Performance Metrics in the Current Practice

The graph below demonstrates a common use of energy performance metrics in the current practice. Please answer the questions below based on your best knowledge or understanding:



- 1) Are you familiar with the metrics and units presented in the graph?
 - a. Extremely familiar
 - b. Very familiar
 - c. Moderately familiar
 - d. Slightly familiar
 - e. Not at all familiar

- 2) How useful do you find these metrics and graph for making decisions about mechanical, electrical and lighting systems?
 - a. Very useful
 - b. Somewhat useful
 - c. Undecided / Neutral
 - d. Not very useful
 - e. Not at all useful

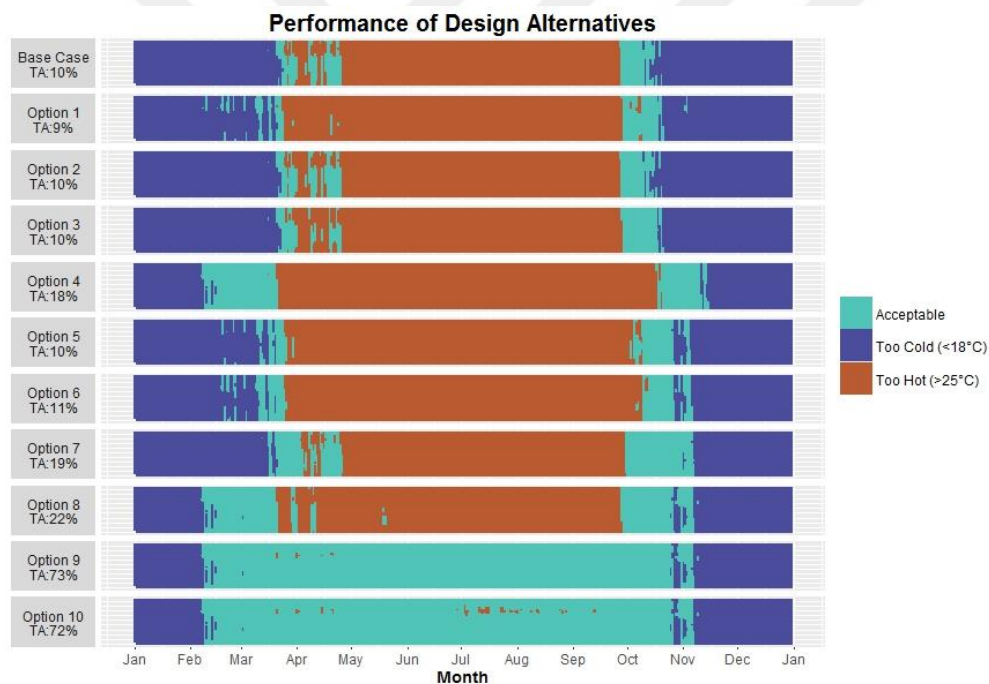
- 3) How useful do you find these metrics and graph for facilitating passive design decisions related to the building envelope?
 - a. Very useful
 - b. Somewhat useful
 - c. Undecided / Neutral
 - d. Not very useful
 - e. Not at all useful

- 4) These graphs (or metrics) are aimed at engineers more than architects:
 - a. Strongly agree
 - b. Agree
 - c. Neither agree or disagree
 - d. Disagree
 - e. Strongly disagree

Interpreting Proposed Thermal Autonomy Graphs

Thermal autonomy (TA) is used as a measure of the fraction of time a building can passively maintain comfort conditions without mechanical heating or cooling. For this analysis, all of the active systems for HVAC, lighting and equipment are turned off in the energy model. Then the analysis consists of identifying the number of hours above and below the given set of thermal comfort acceptability criteria through passive means only.

The proposed use of thermal autonomy analysis demonstrated in the TA graph below. Please answer the following questions based on your best understanding:



- 1) Do you understand the graph? If not, why not?

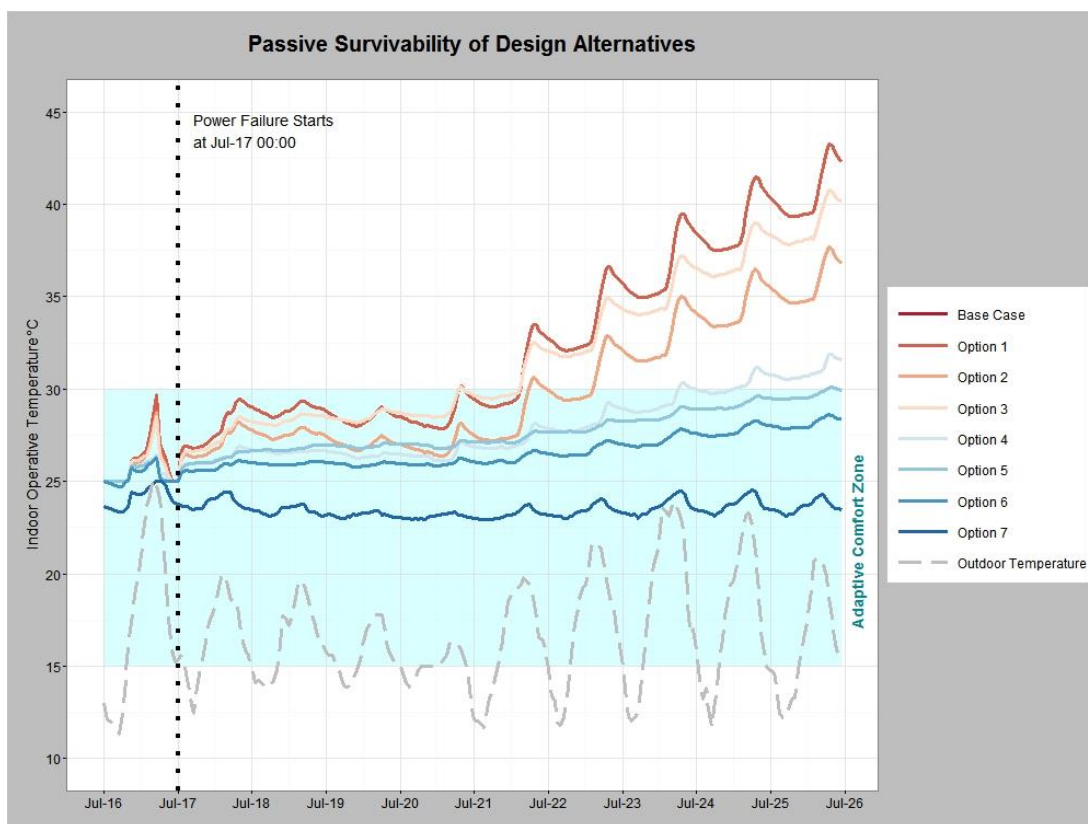
- 2) Which design option does cause the most overheating?
 - a. Option 1
 - b. Option 3
 - c. Option 4
 - d. None of the above.
 - e. I don't understand the graph.

- 3) Which design option does provide the shortest comfortable period?
- Option 1
 - Option 2
 - Option 3
 - Option 4
 - I don't understand the graph.
- 4) To what extent do you agree or disagree with the following statements regarding the use of TA graphs for facilitating decision making during the early design stage? (Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree)
- TA graphs indicate how a building design might perform independent from mechanical systems.
 - TA graphs give an idea when or if mechanical systems can be turned off.
 - TA graphs show daily and seasonal patterns.
 - TA graphs predict occupant comfort.
 - TA graphs are effective in visualizing building-level passive design strategies.
 - TA graphs have temporal resolution that is sufficient to understand the building's energy performance.
 - TA graphs are useful for facilitating passive systems design decision making.
 - If TA graphs were available to me at the early stages of my building designs, I would use them.
 - TA graphs are intuitive.
- 5) How could the Thermal Autonomy graphs be improved to be more useful to visualize the effect of passive design strategies on the building level?
-

Interpreting Proposed Passive Survivability Graphs

Passive survivability (PS) is used as a measure of how long inhabitants may remain in their dwellings during extended power outages that coincide with extreme weather events. For this analysis, all active systems are shut off during a period of extreme summer or winter weather. Comparative results among various passive strategies enable the designer to assess the passive survivability of the building under these conditions.

The PS graph below is based on an energy simulation assumes a power failure that occurs on July 17th and tracks the indoor temperature up until July 25th based on various passive performance. Please answer the questions below based on your best understanding:



- 1) Do you understand the graph? If not, why not?
- 2) From the graph above, which passive strategy provides the longest period of tolerable interior temperatures after a power failure?
 - a. Option 1
 - b. Option 3
 - c. Option 5
 - d. Non of the above.
 - e. I don't understand the graph.
- 3) To what extent do you agree or disagree with the following statements regarding the use of the PS graph above for facilitating decision making at the

early design stage? (Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree)

- PS graphs indicate how a building design might perform independently from mechanical systems.
- PS graphs predict occupant comfort.
- PS graphs are effective in visualizing building-level passive design strategies.
- PS graphs have temporal resolution that is sufficient to understand the indoor comfort conditions during extended power system failures.
- PS graphs are useful for improving resilient design decisions.
- If PS graphs like the one shown above were available to me at the early design stages of my building(s), I would use them.
- PS graphs are intuitive.

- 4) How could the Passive Survivability graphs be improved to be more useful to visualize the effect of passive design strategies on the building level?

.....

General Questions

Now that you have had an opportunity to compare conventional energy performance metrics [peak energy demand (kW), annual energy consumption (kWh) and energy use intensity (kWh/m².year)] and time based metrics like Thermal Autonomy and Passive Survivability, please answer the following questions.

- 1) For the design of passive systems such as the building envelope and fenestration for natural ventilation and daylighting, the most useful metrics at the early stages of building design are:
 - a. Conventional metrics (kW, kWh and kWh/m².year).
 - b. Thermal Autonomy (TA) and Passive Survivability (PA).
 - c. Both are useful at the early stages of design decision making.
 - d. I cannot decide between the two types of metrics.
 - e. I don't know enough about energy performance modelling to decide.
 - f. Other
- 2) If the visualization of time-based metrics for other performance parameters was available, indicate which of the following you would find helpful at the early stages of building design:
 - Daylighting.
 - Thermal Comfort.
 - Indoor Air Quality.
 - Acoustics.
 - Occupancy
 - Other
- 3) Do you have any other comments?

Thank you!

Thank you for taking the time to provide your valuable input. If you are satisfied with your responses, you may submit them now! The results will be securely and anonymously stored. Your information will not be shared with anyone. Shortly thereafter, we expect the aggregate and anonymous results to be published in a journal article.



Appendix B : Thermal Autnomy Graphs

In chapter 4, thermal autonomy results are visualized for units in south (both 80% and 40% WWR) and north (only 80% WWR) orientations in each location. The rest of the visualizations are presented below. The results are already discussed in Chapter 4 showing them in a table format.



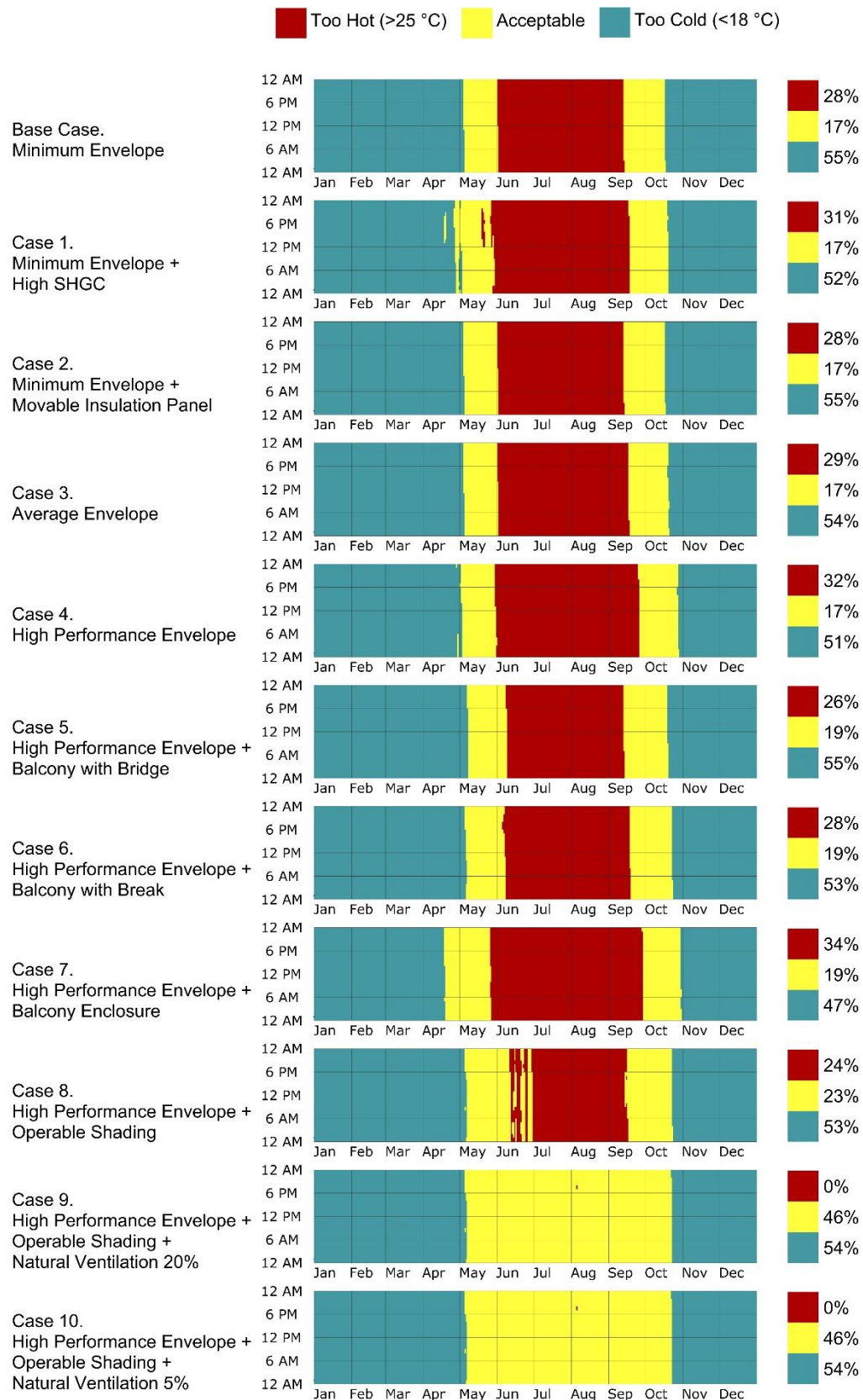


Figure B.1 : Thermal autonomy performance of a north-facing unit with 40% WWR in Toronto, Canada.

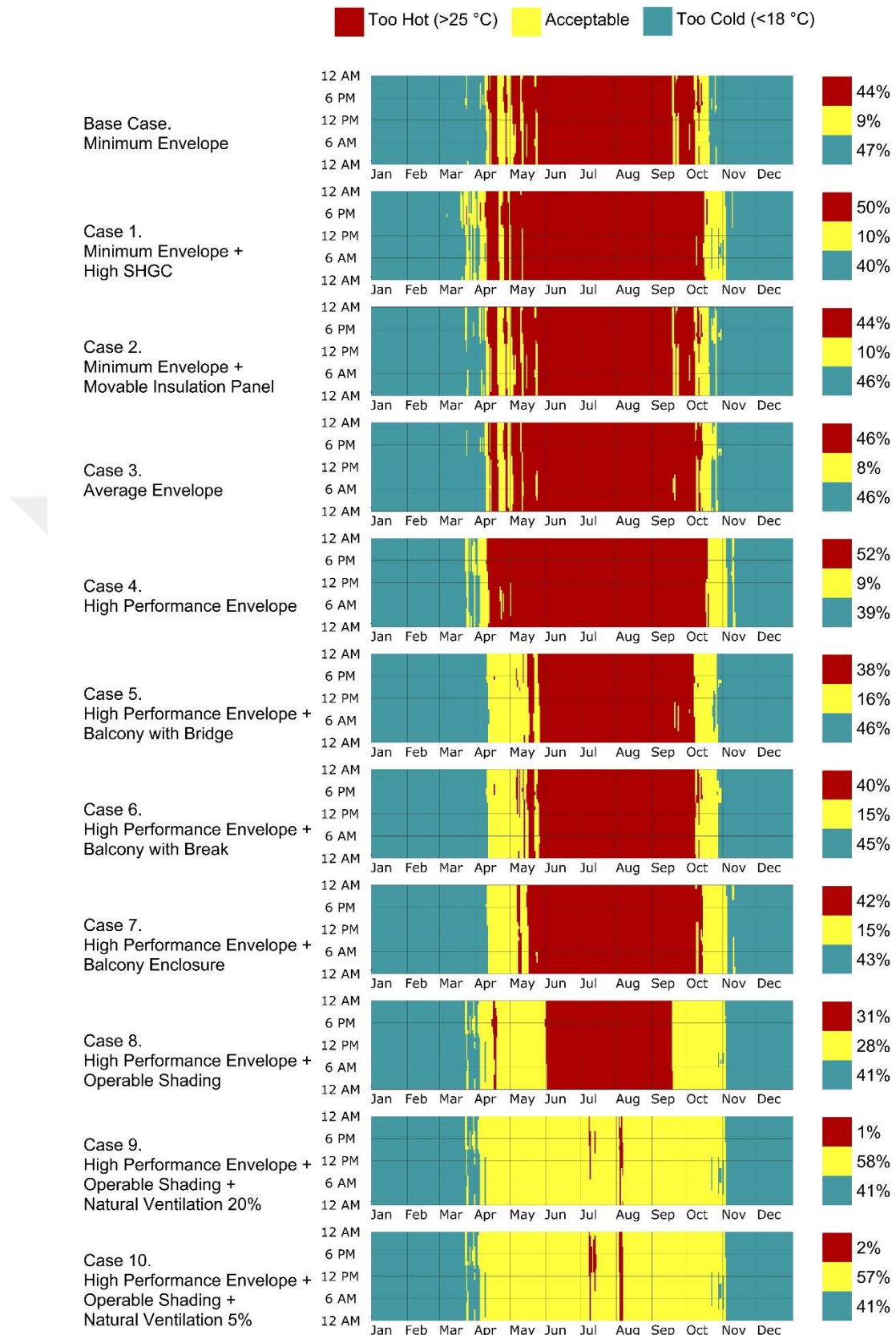


Figure B.2 : Thermal autonomy performance of a west-facing unit with 80% WWR in Toronto, Canada.

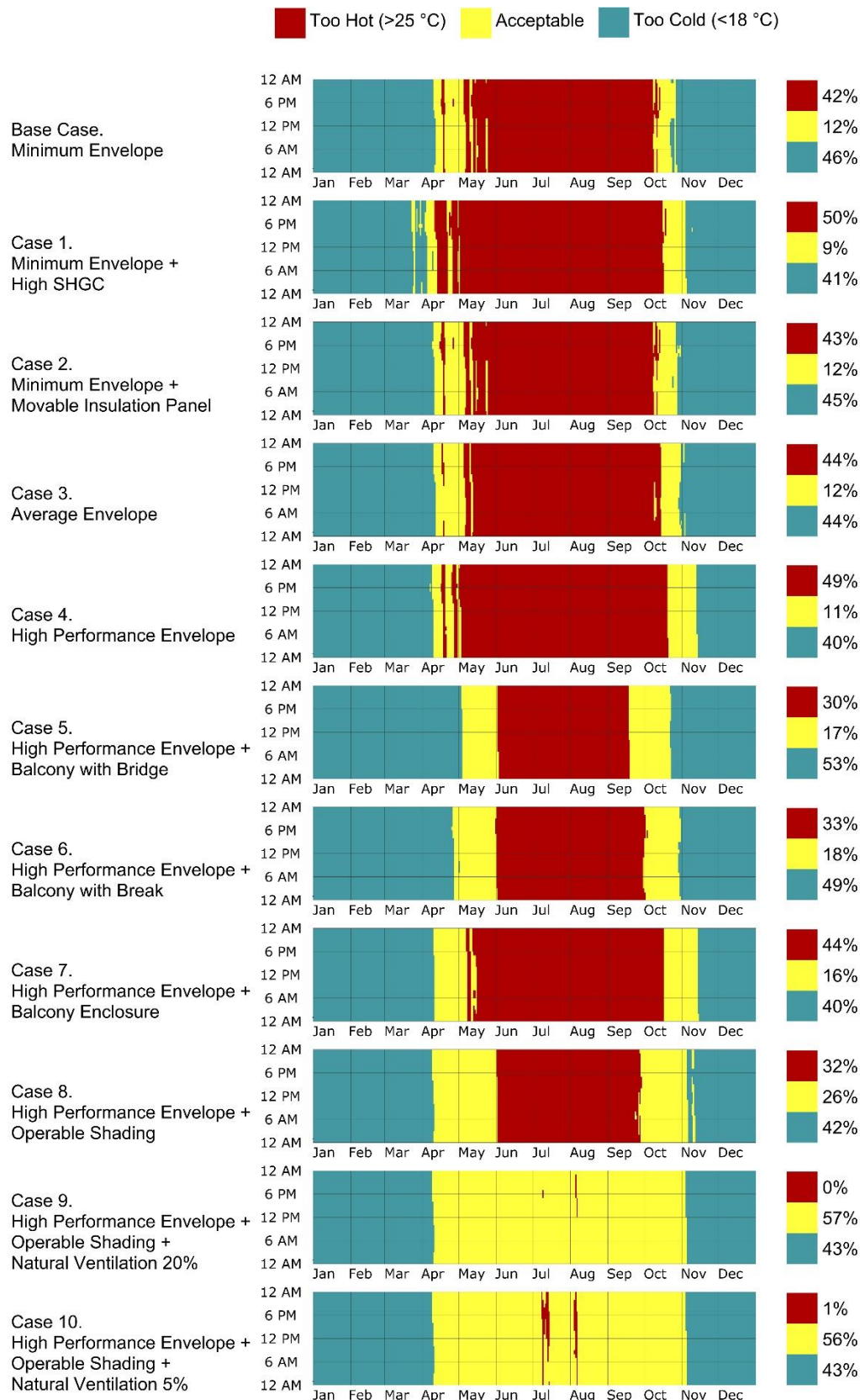


Figure B.3 : Thermal autonomy performance of a west-facing unit with 40% WWR in Toronto, Canada.

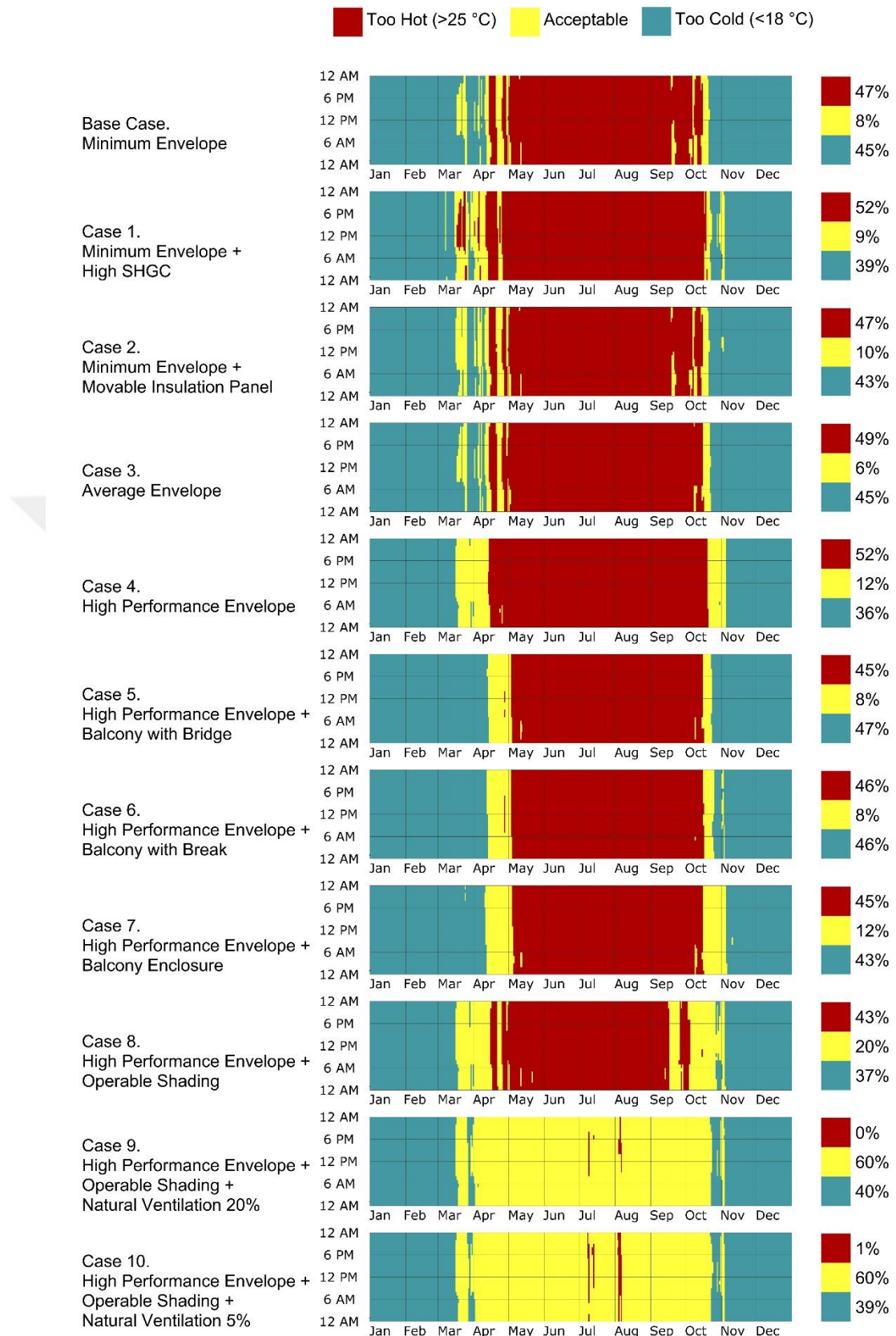


Figure B.4 : Thermal autonomy performance of an east-facing unit with 80% WWR in Toronto, Canada.

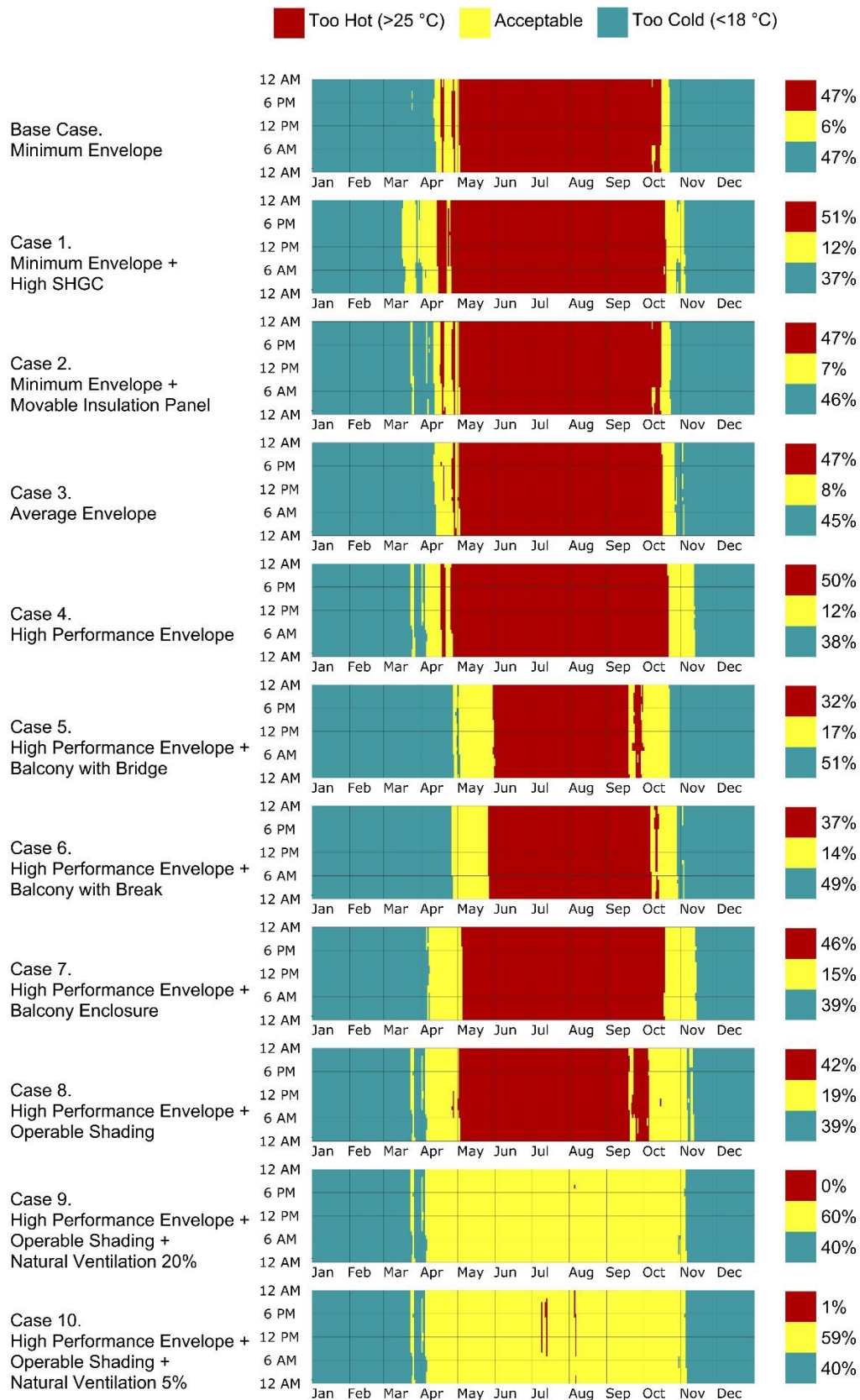


Figure B.5 : Thermal autonomy performance of an east-facing unit with 40% WWR in Toronto, Canada.

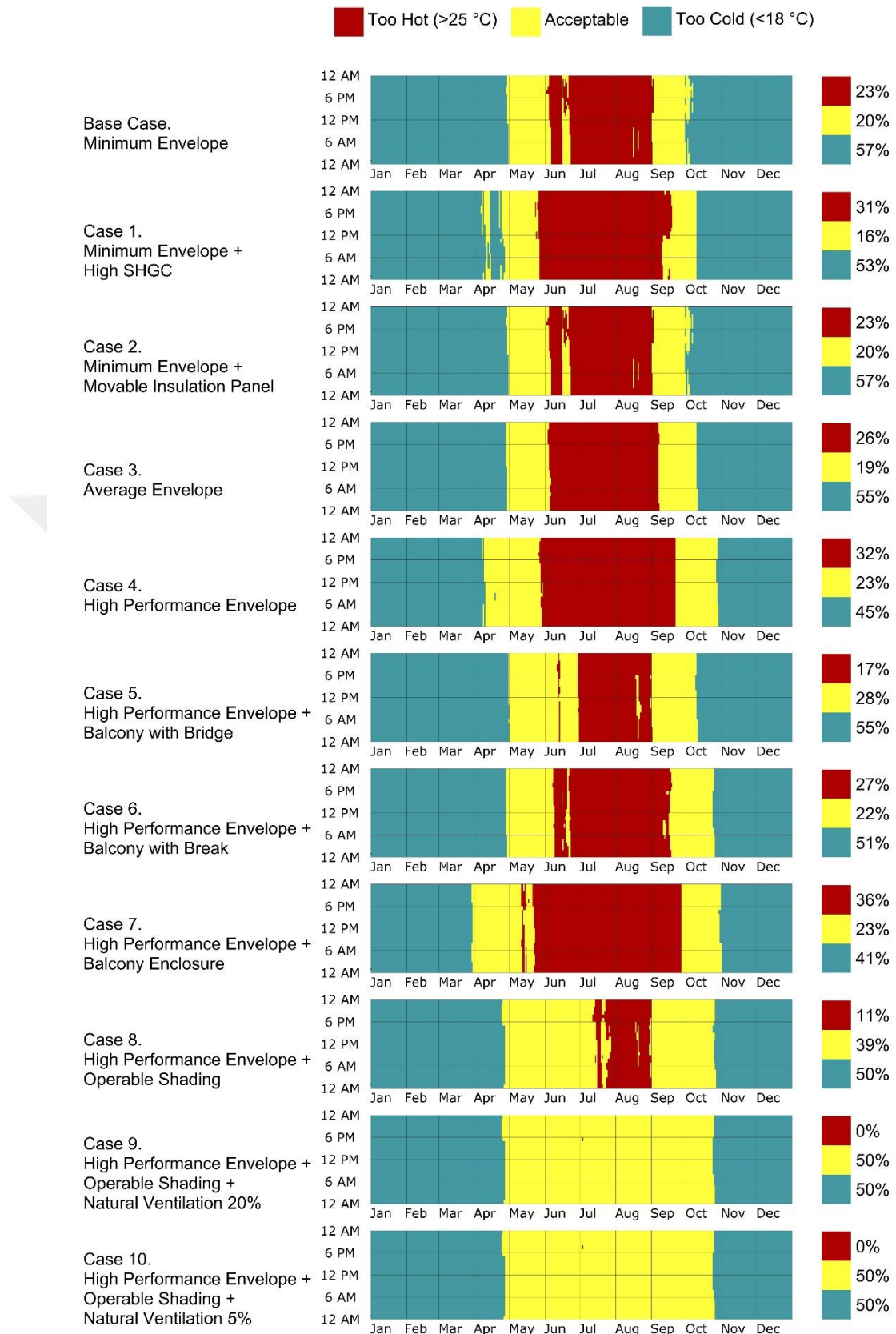


Figure B.6 : Thermal autonomy performance of a north-facing unit with 40% WWR in Vancouver, Canada.

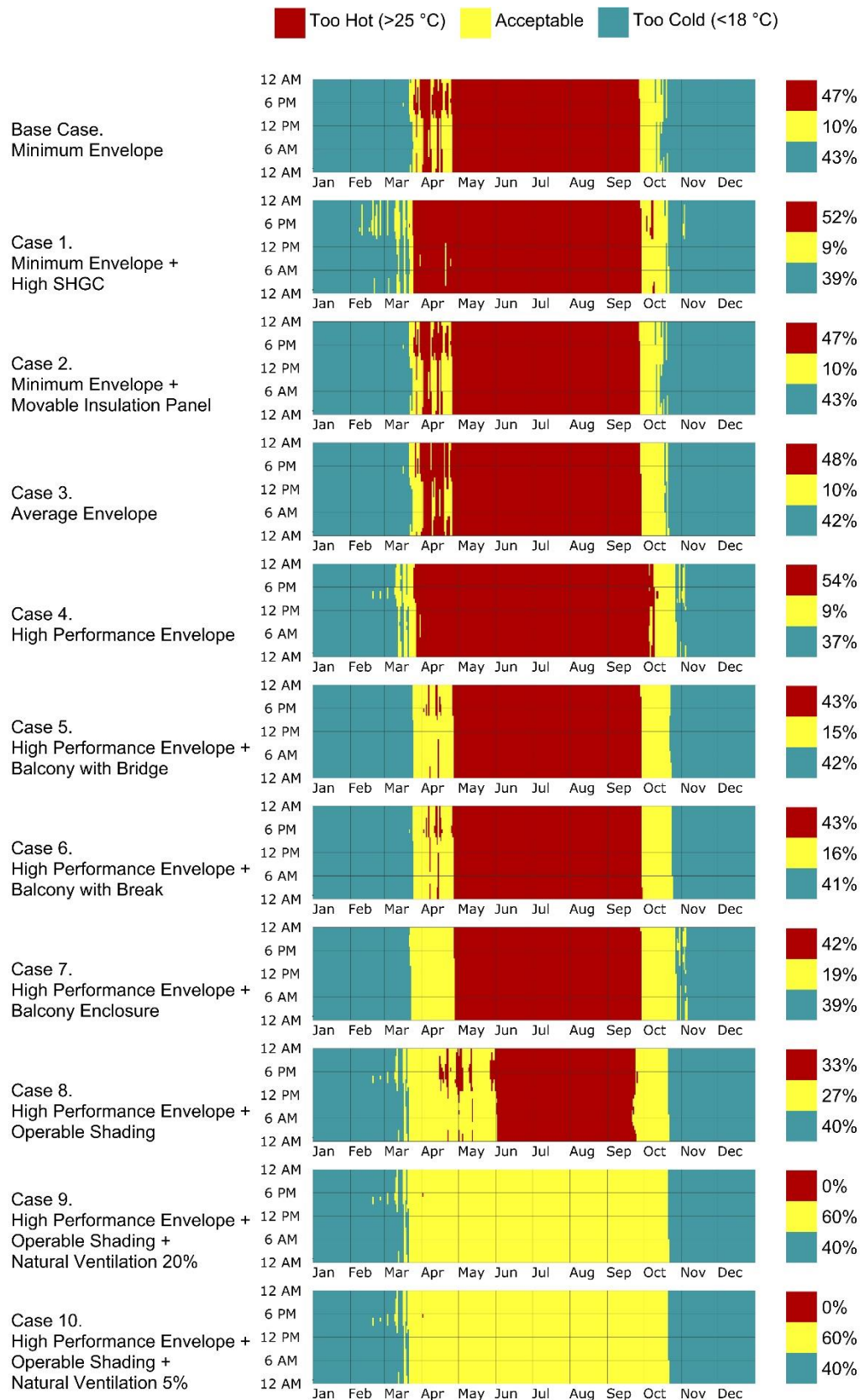


Figure B.7 : Thermal autonomy performance of a west-facing unit with 80% WWR in Vancouver, Canada.

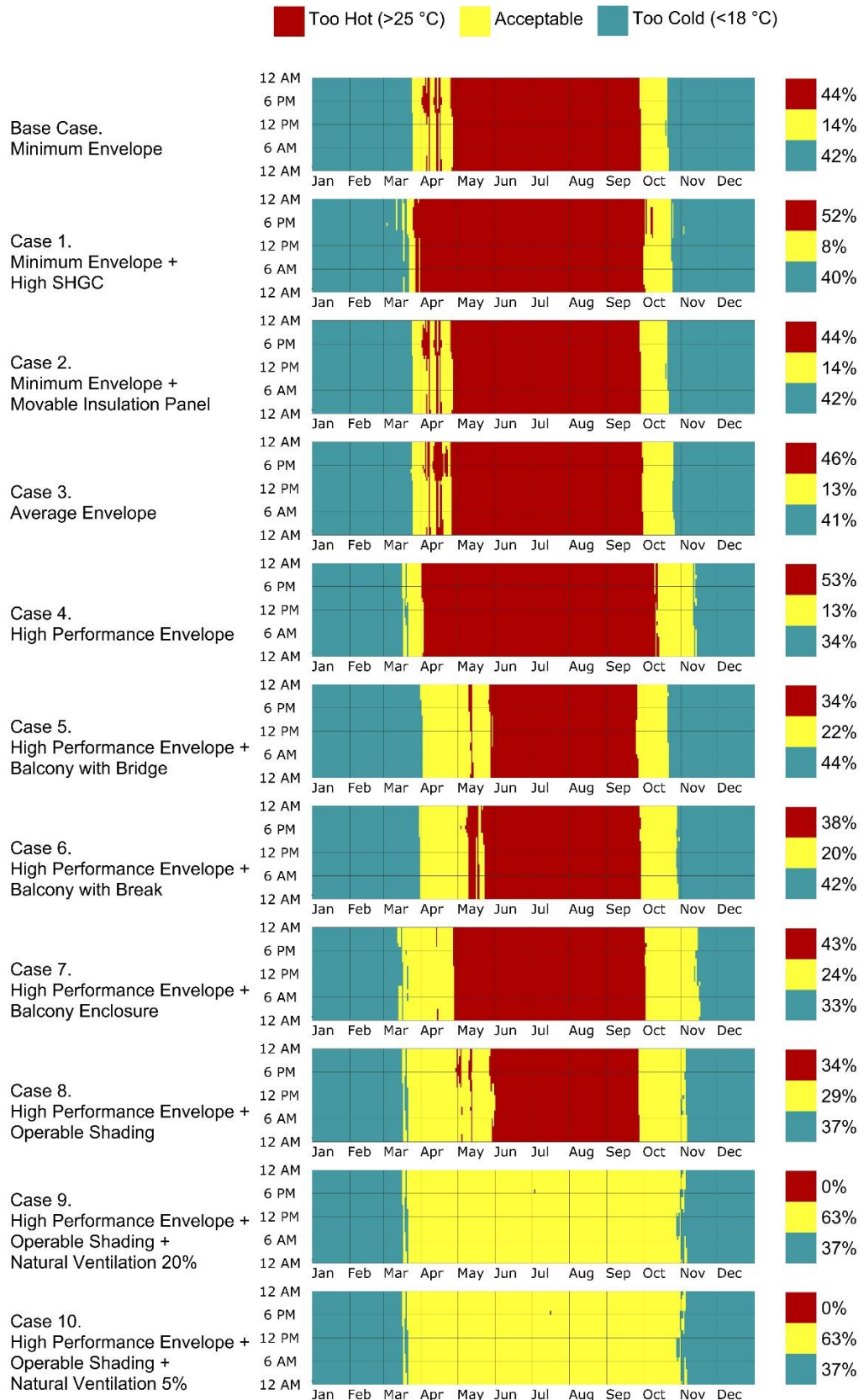


Figure B.8 : Thermal autonomy performance of a west-facing unit with 40% WWR in Vancouver, Canada.

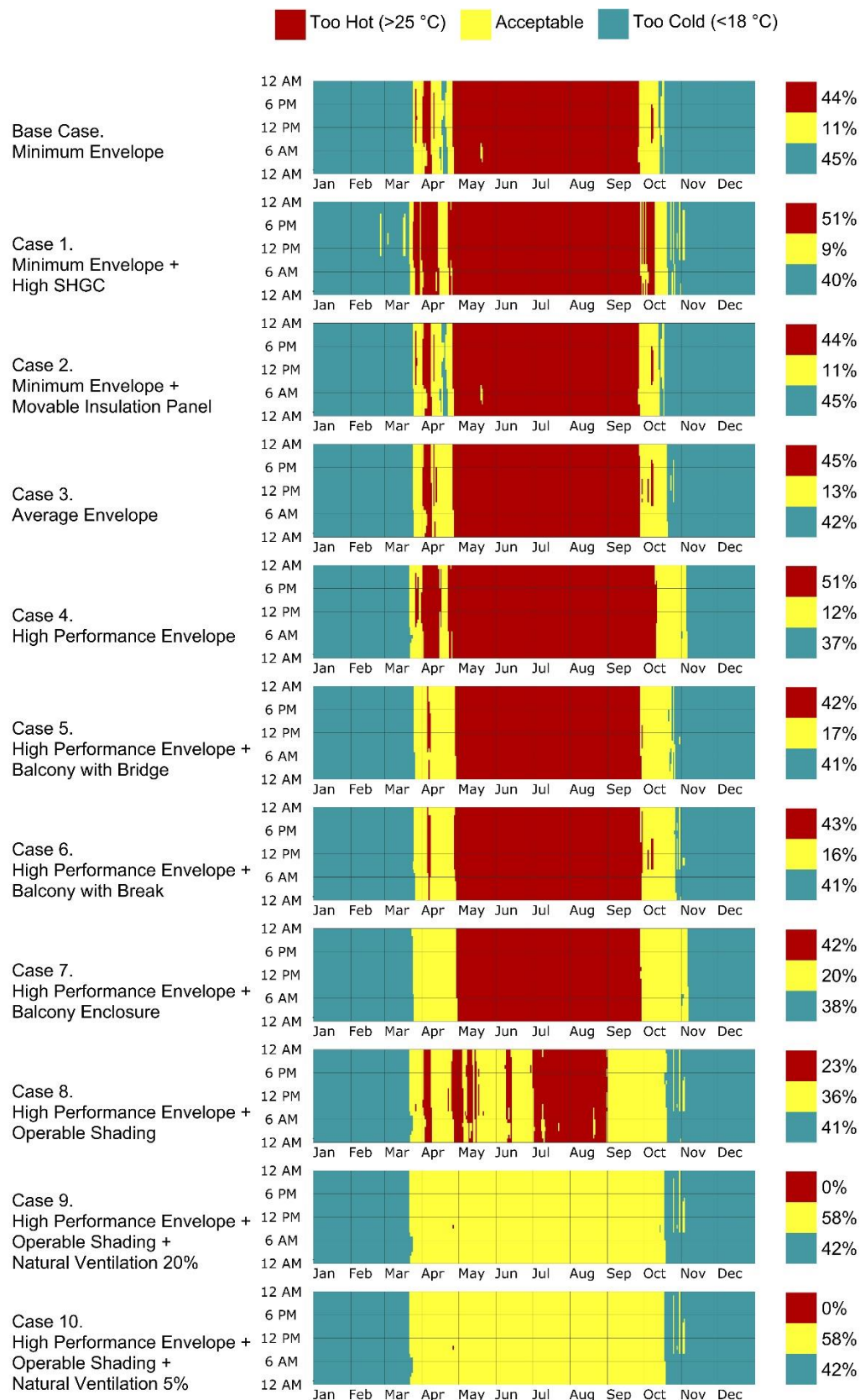


Figure B.9 : Thermal autonomy performance of an east-facing unit with 80% WWR in Vancouver, Canada.

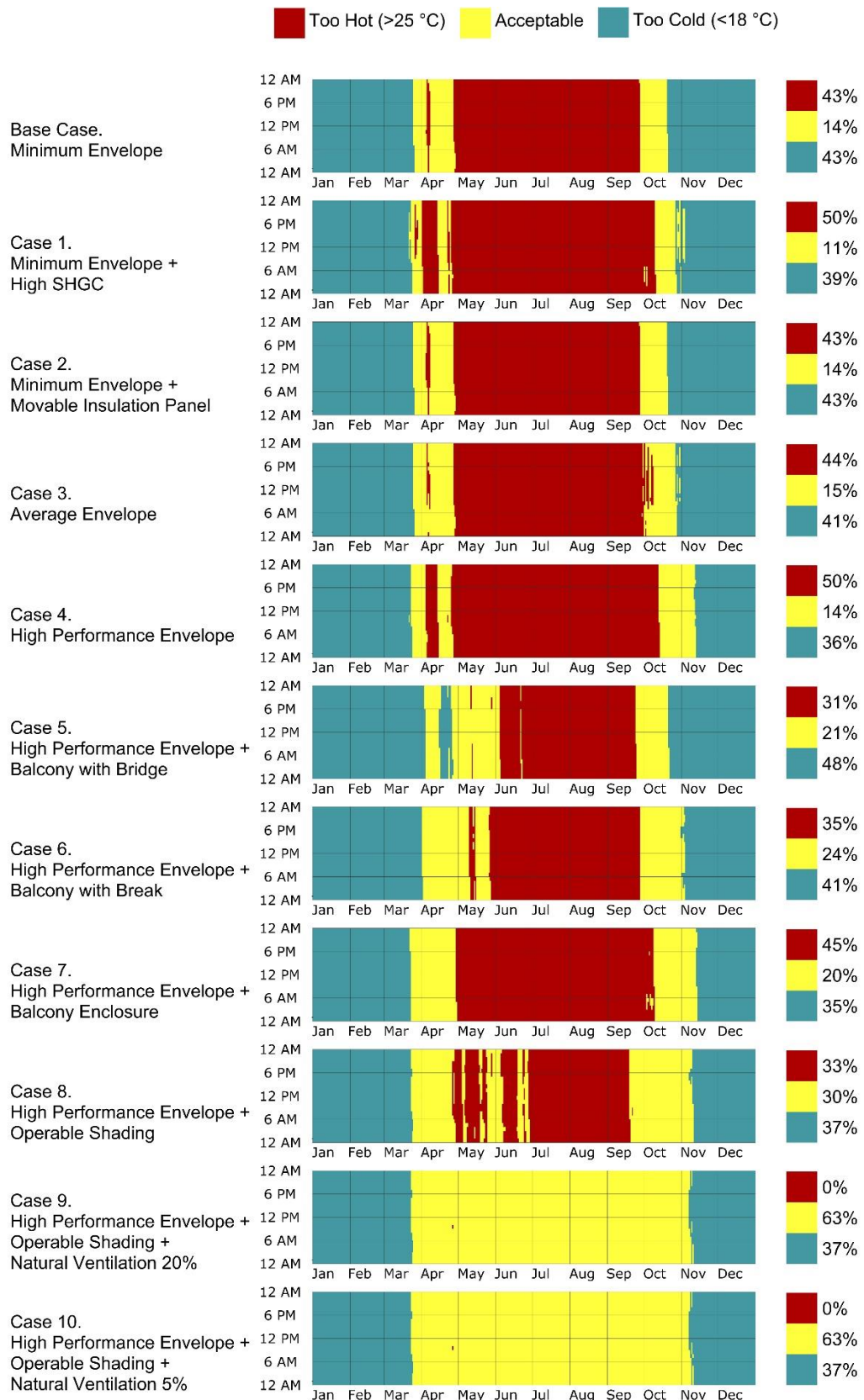


Figure B.10 : Thermal autonomy performance of an east-facing unit with 40% WWR in Vancouver, Canada.

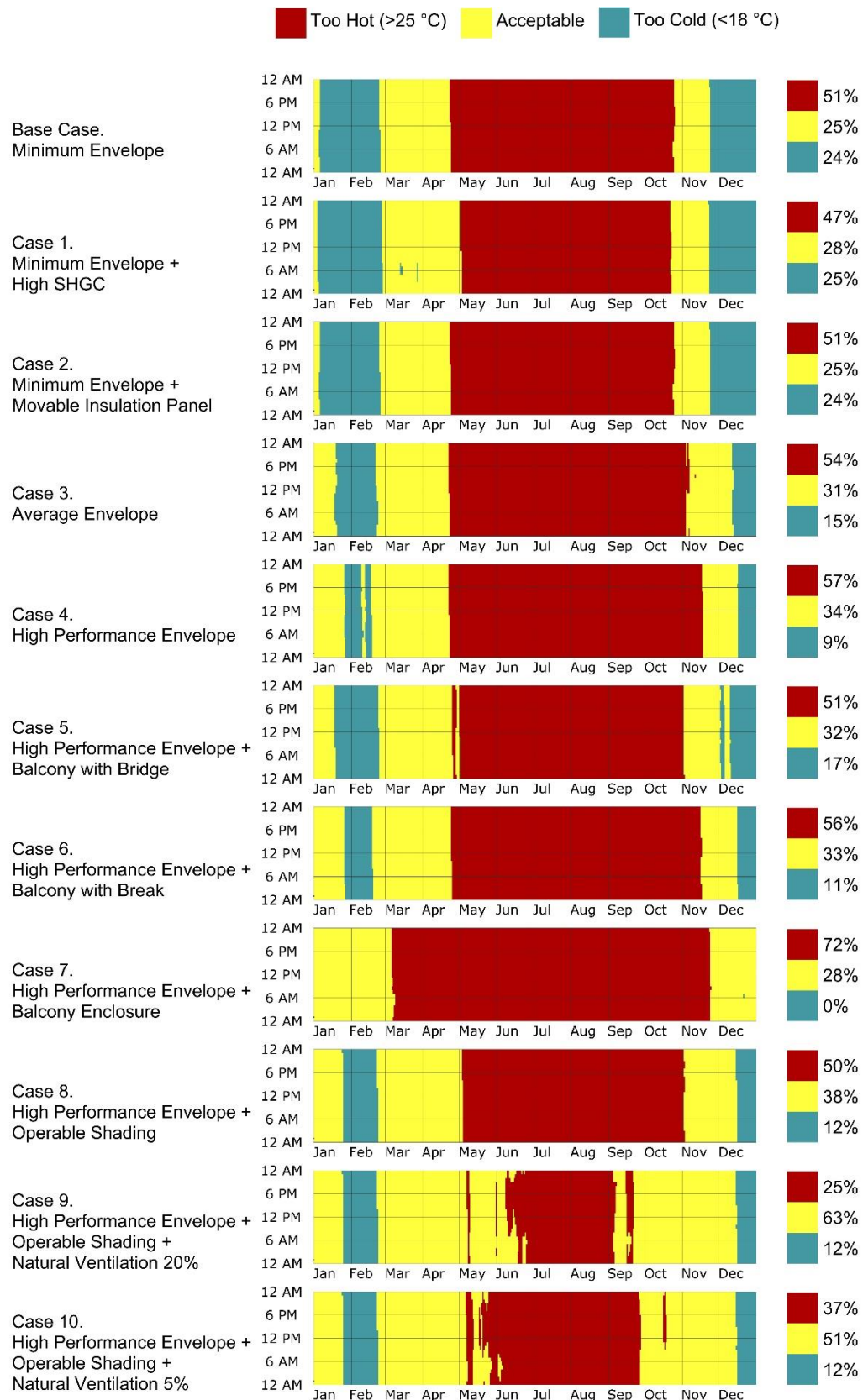


Figure B.11 : Thermal autonomy performance of a north-facing unit with 30% WWR in Adana, Turkey.

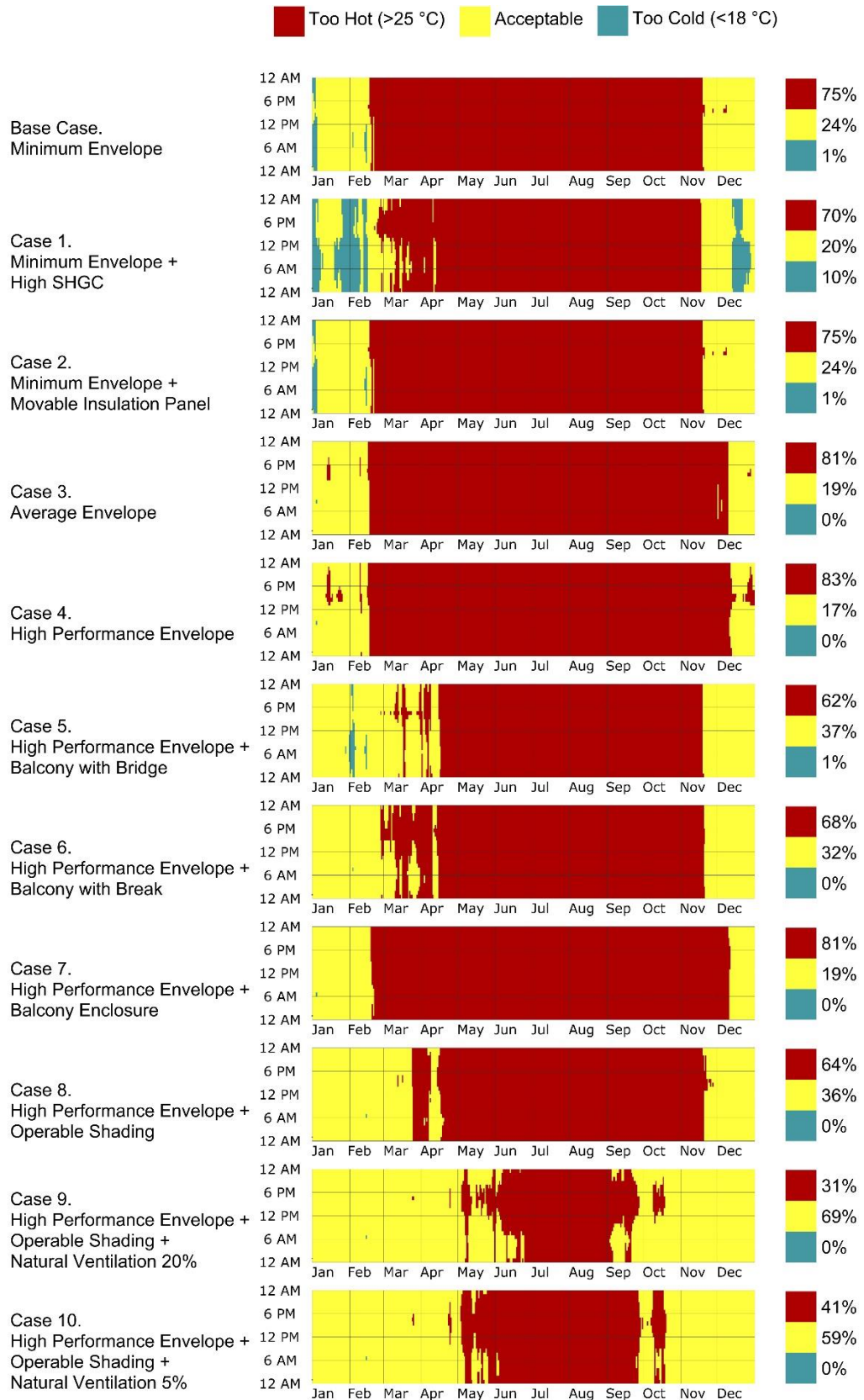


Figure B.12 : Thermal autonomy performance of a west-facing unit with 60% WWR in Adana, Turkey.

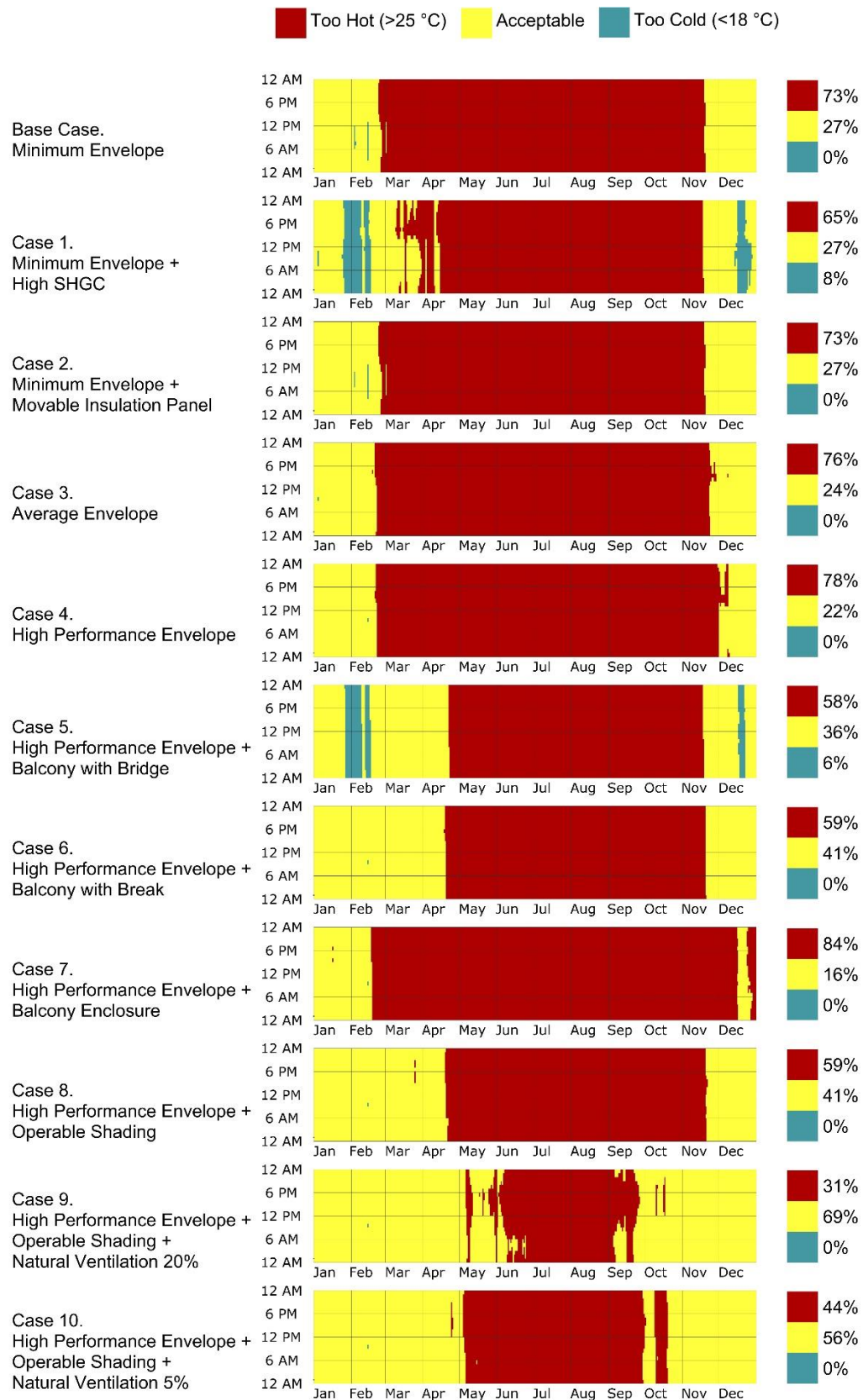


Figure B.13 : Thermal autonomy performance of a west-facing unit with 30% WWR in Adana, Turkey.

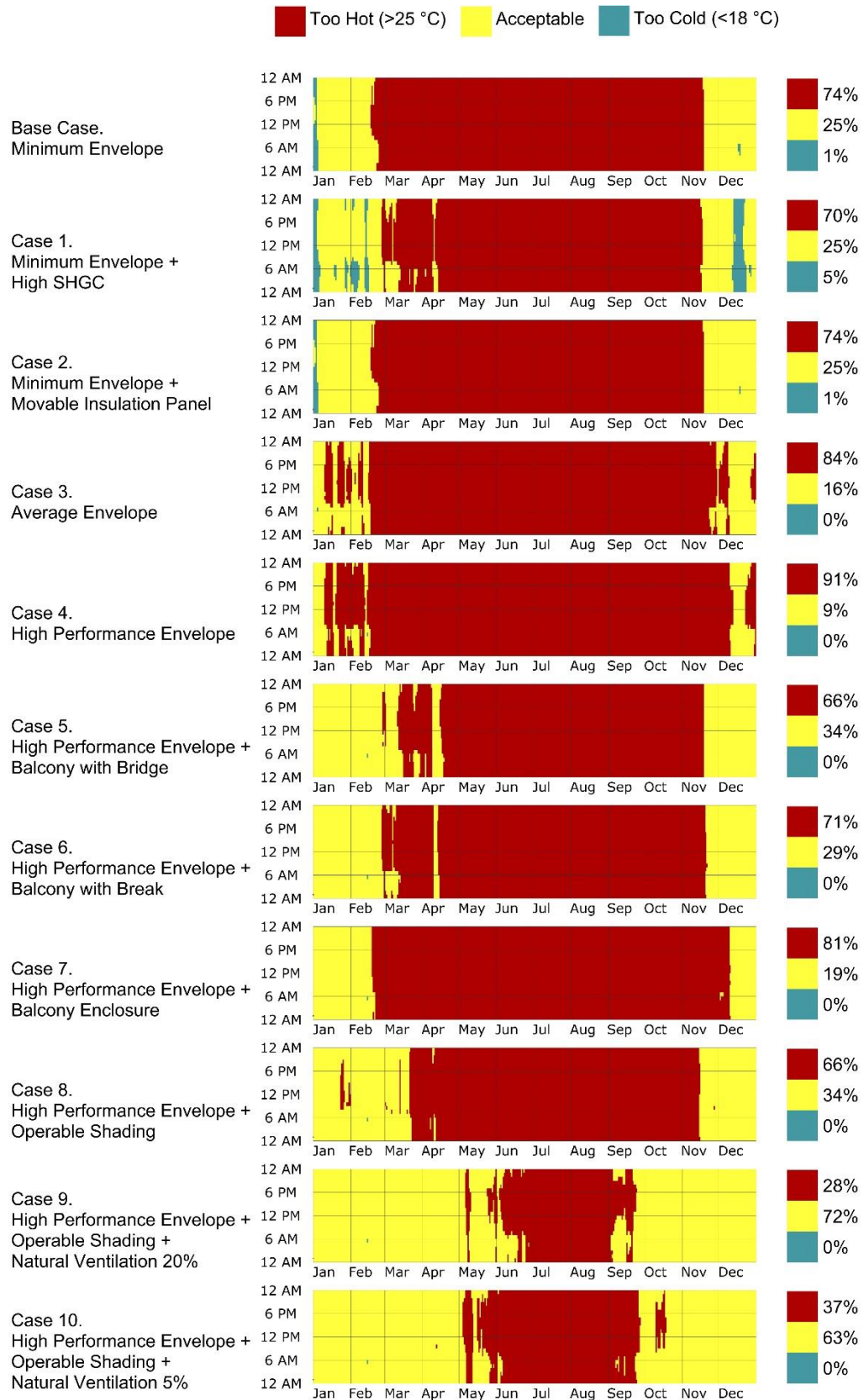


Figure B.14 : Thermal autonomy performance of an east-facing unit with 60% WWR in Adana, Turkey.

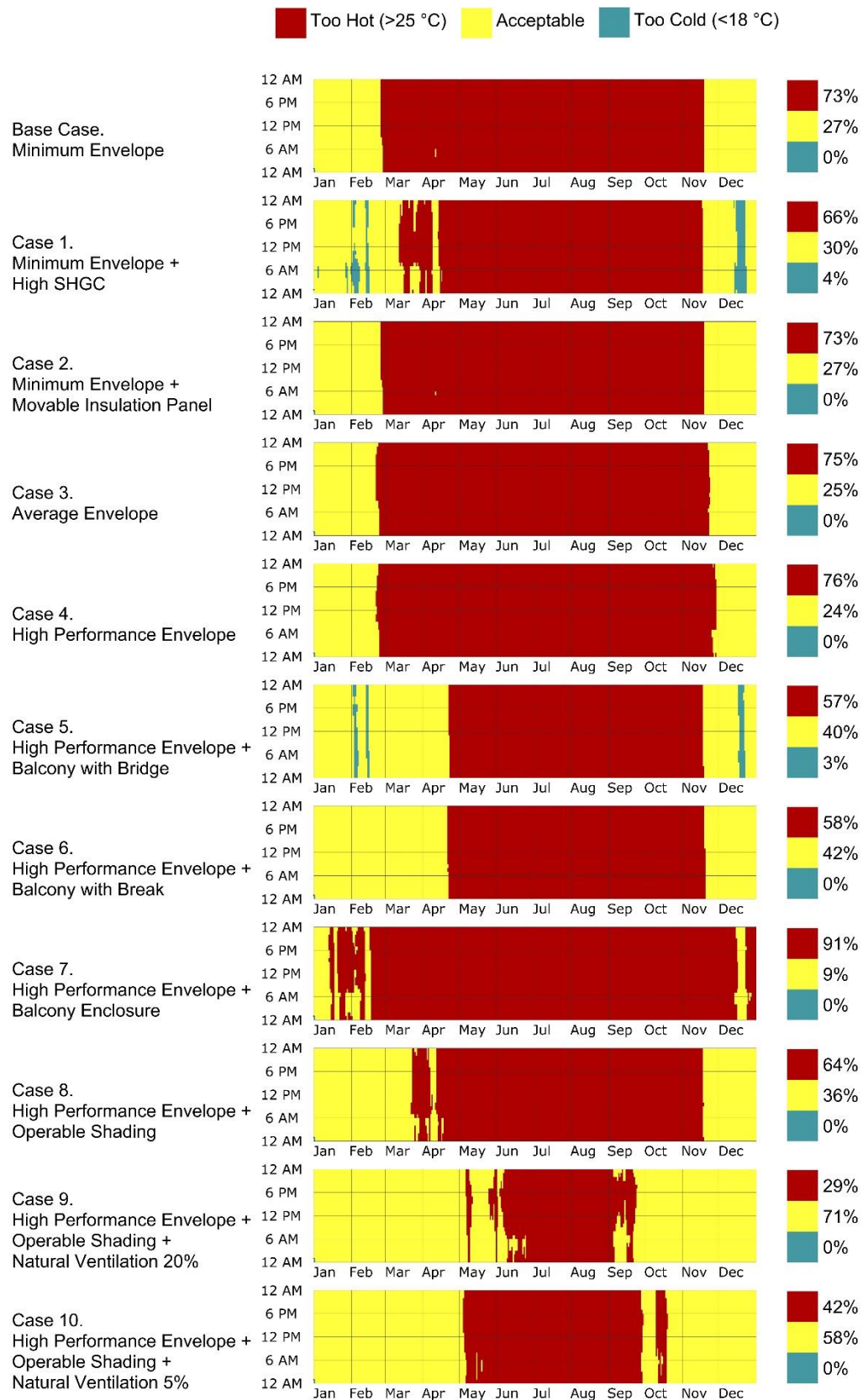


Figure B.15 : Thermal autonomy performance of a north-facing unit with 30% WWR in Adana, Turkey.

APPENDIX C : Passive Survivability Graphs

In chapter 4, demonstrative passive survivability results are visualized for units in south and north orientations with 80%WWR in Toronto. The rest of the visualizations are presented below.

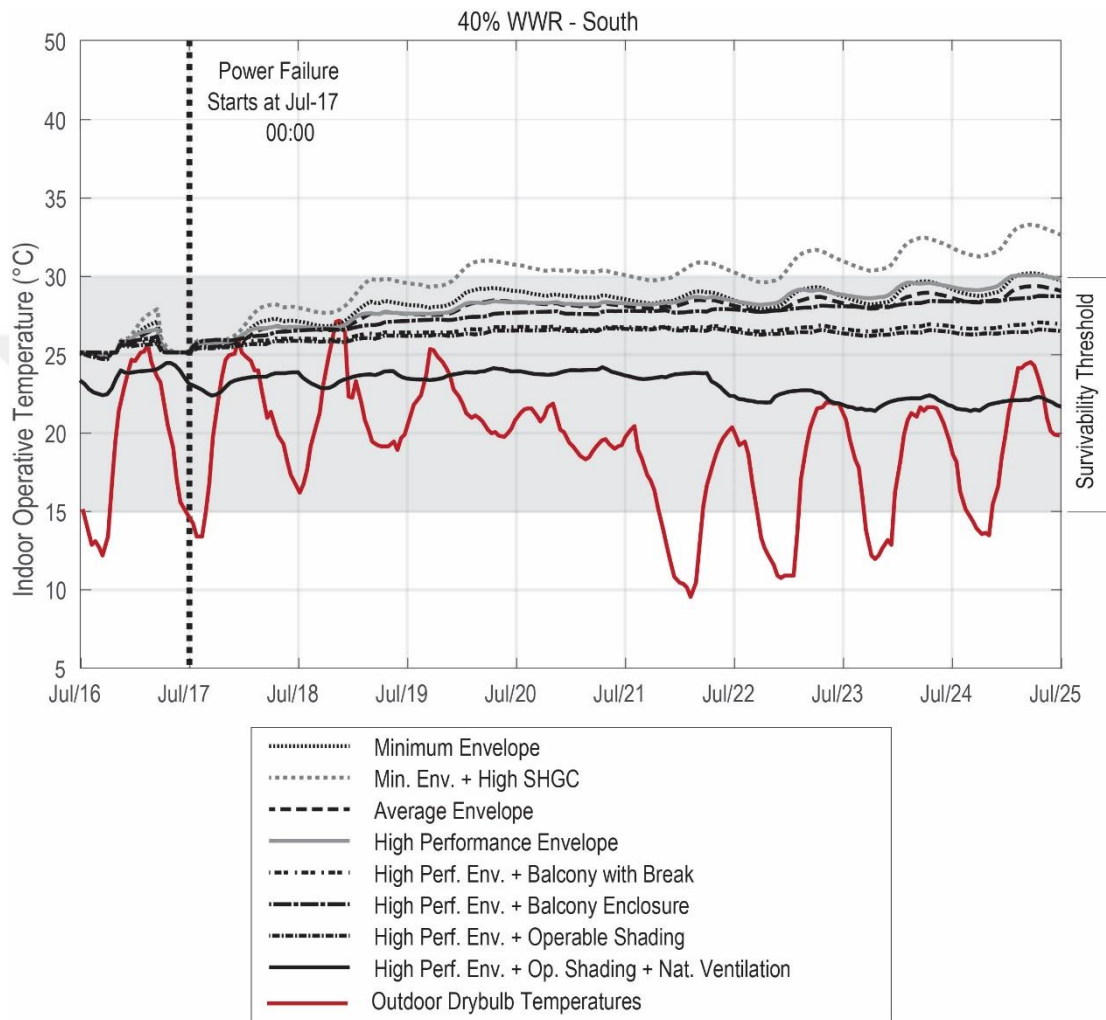


Figure C.1 : Passive survivability performance for a south-facing unit with 40% WWR under summer conditions in Toronto.

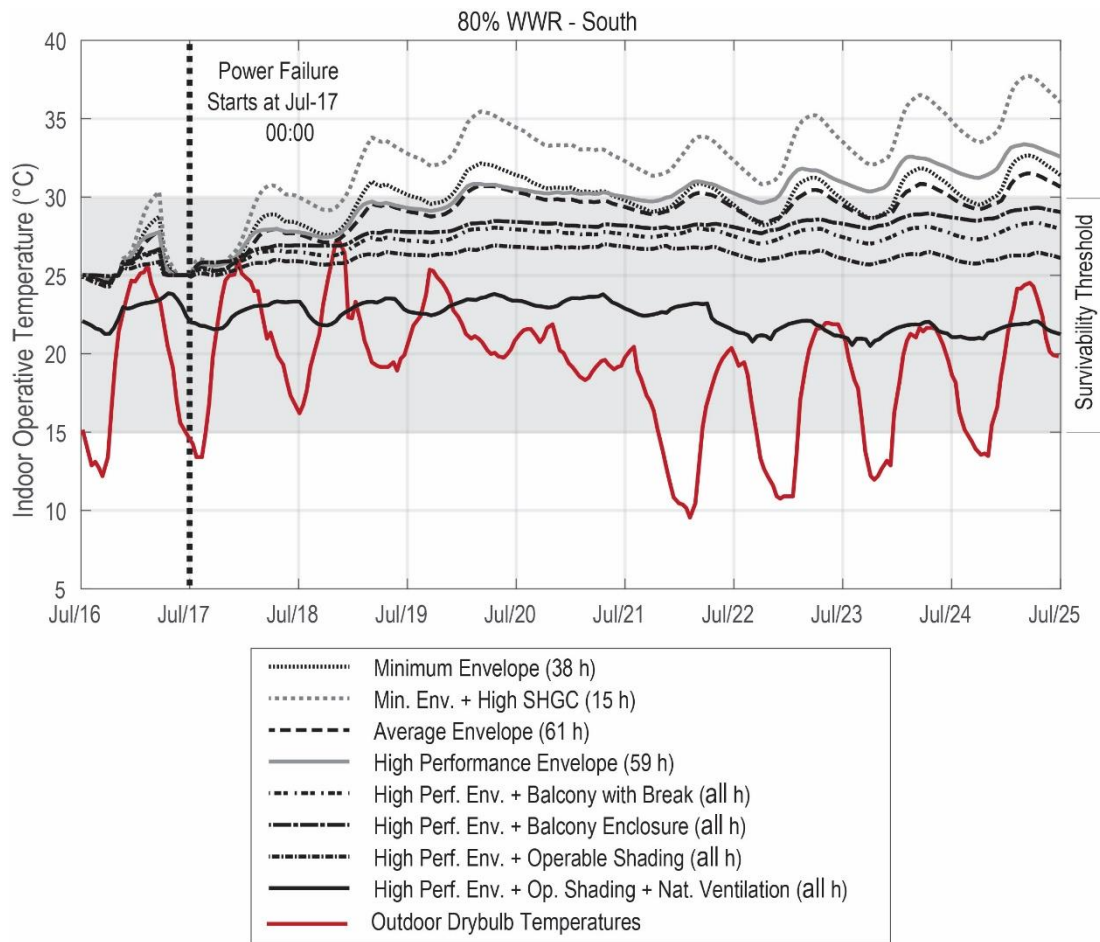


Figure C.2 : Passive survivability performance for a south-facing unit with 80% WWR under summer conditions in Toronto.

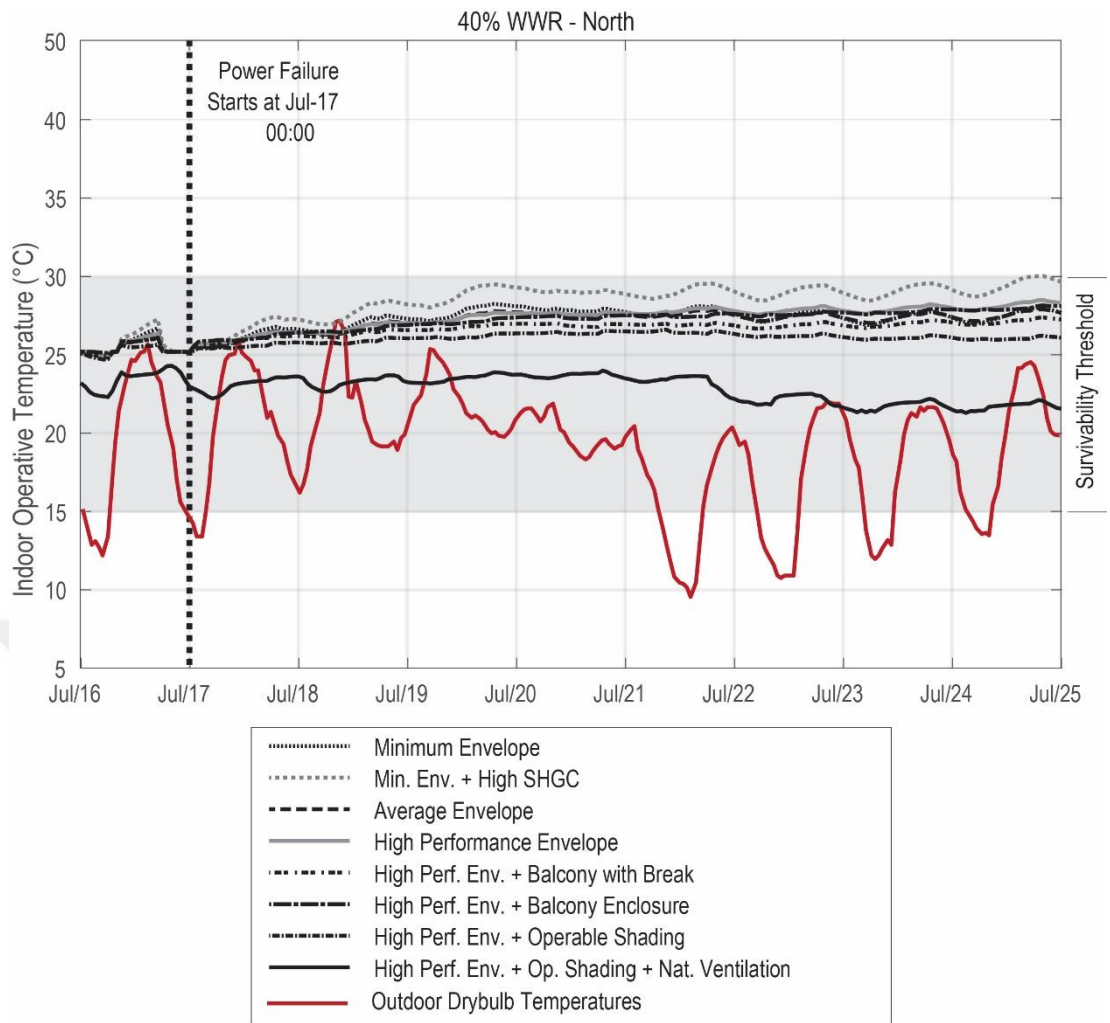


Figure C.3 : Passive survivability performance for a north-facing unit with 40% WWR under summer conditions in Toronto.

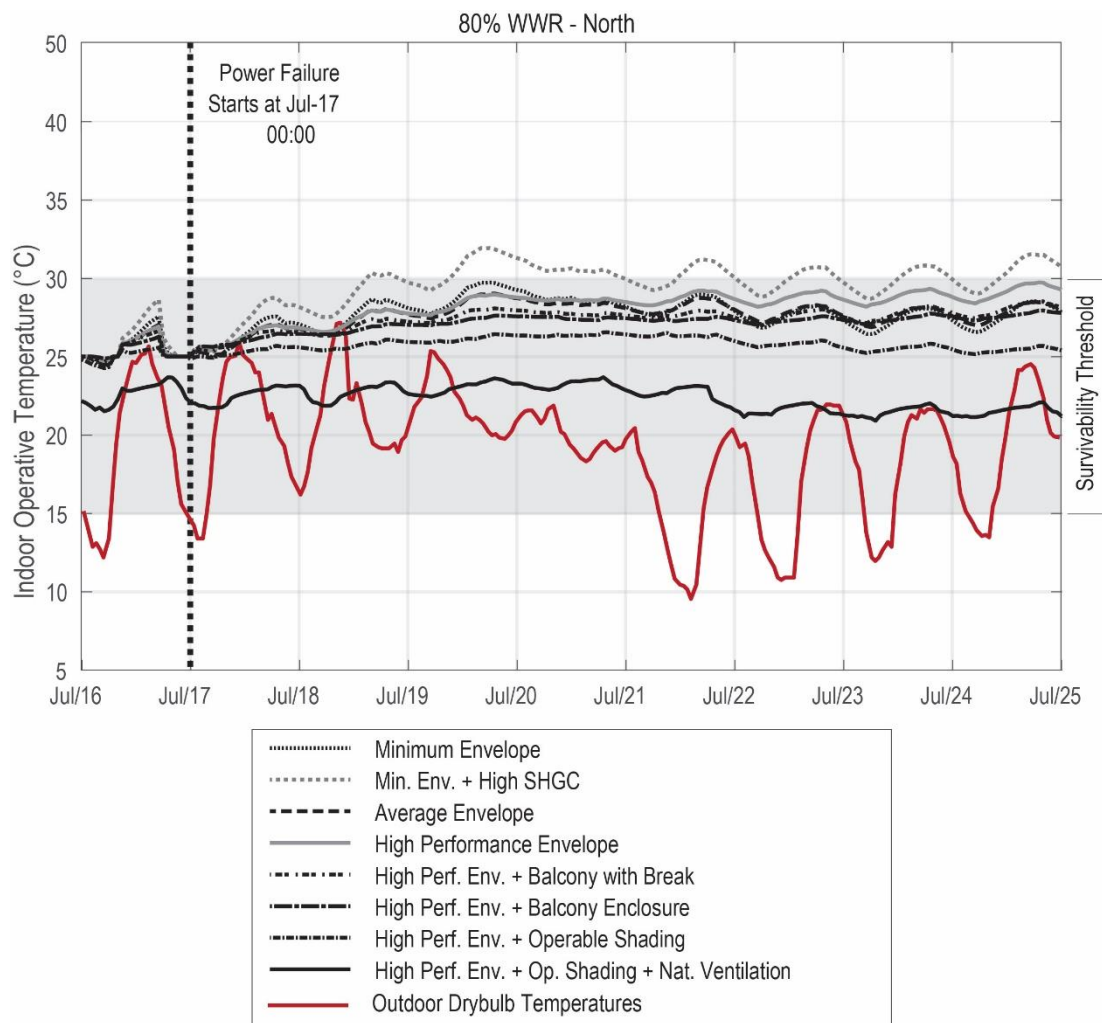


Figure C.4 : Passive survivability performance for a north-facing unit with 80% WWR under summer conditions in Toronto.

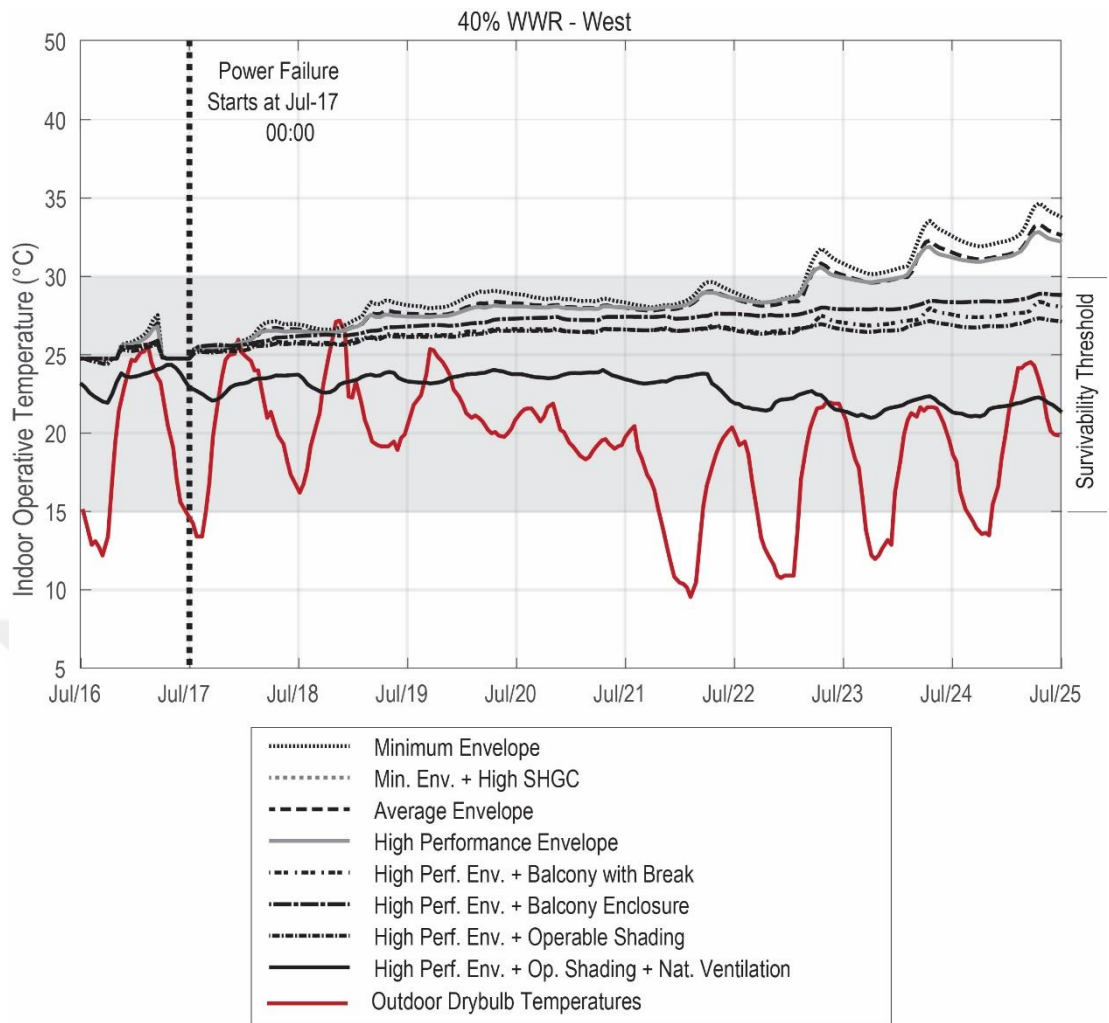


Figure C.5 : Passive survivability performance for a west-facing unit with 40% WWR under summer conditions in Toronto.

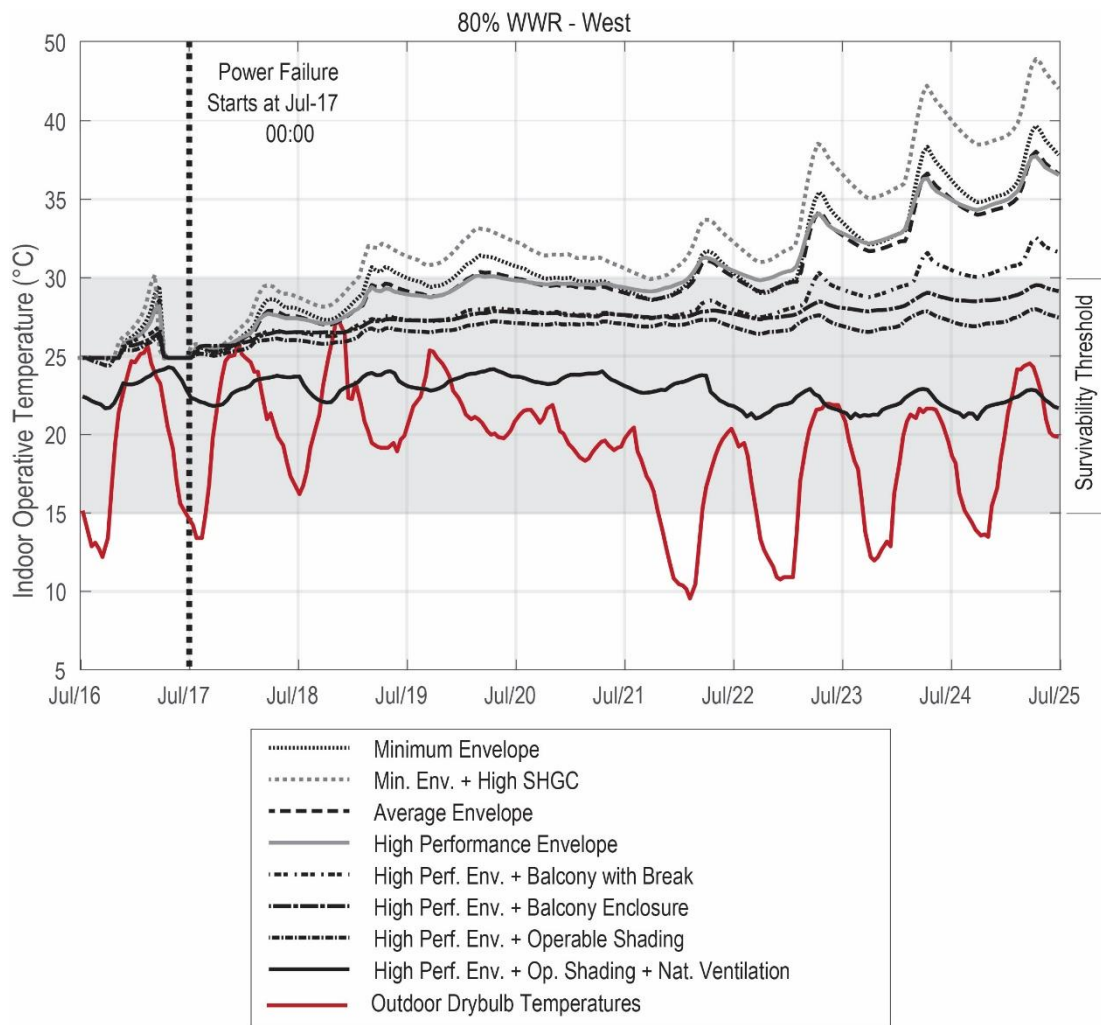


Figure C.6 : Passive survivability performance for a west-facing unit with 80% WWR under summer conditions in Toronto.

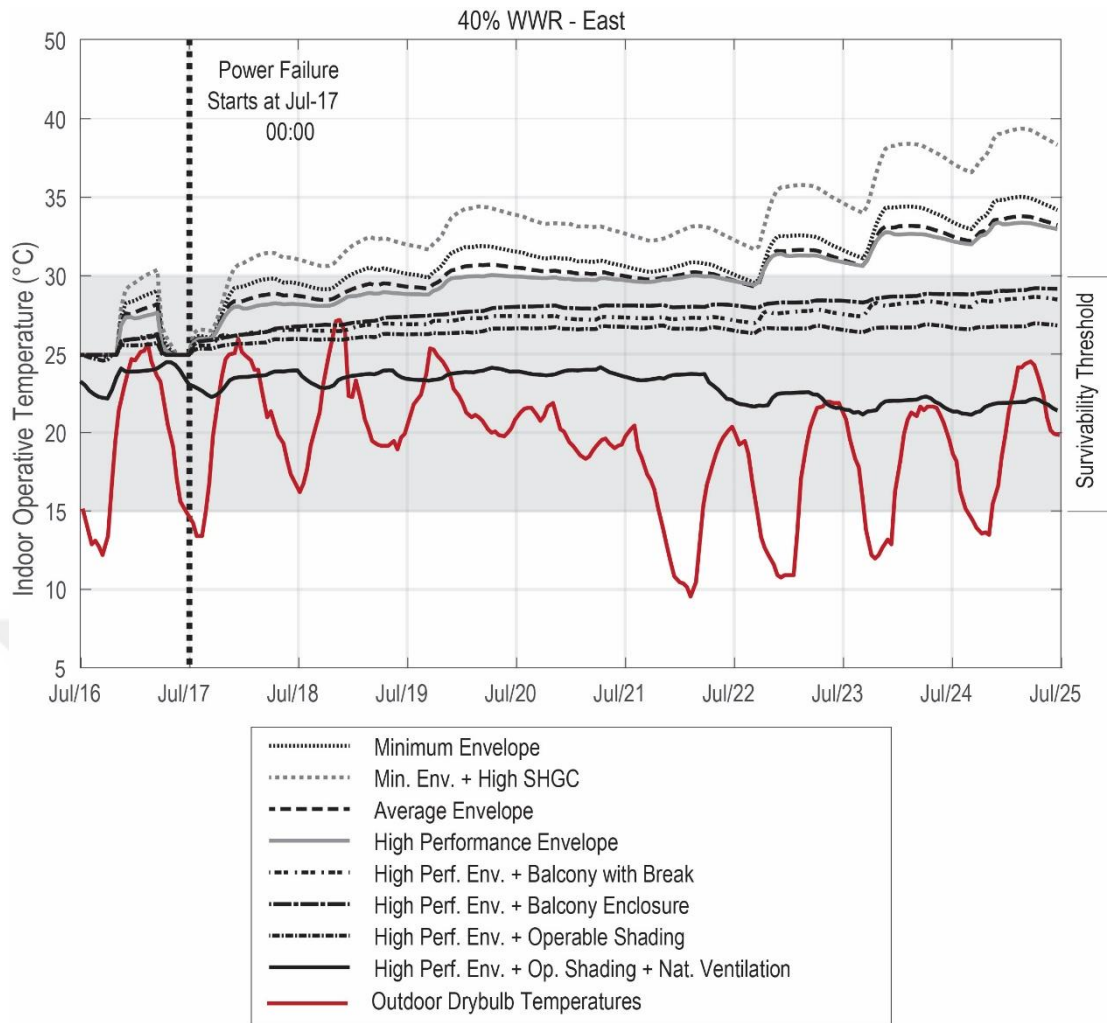


Figure C.7 : Passive survivability performance for an east-facing unit with 40% WWR under summer conditions in Toronto.

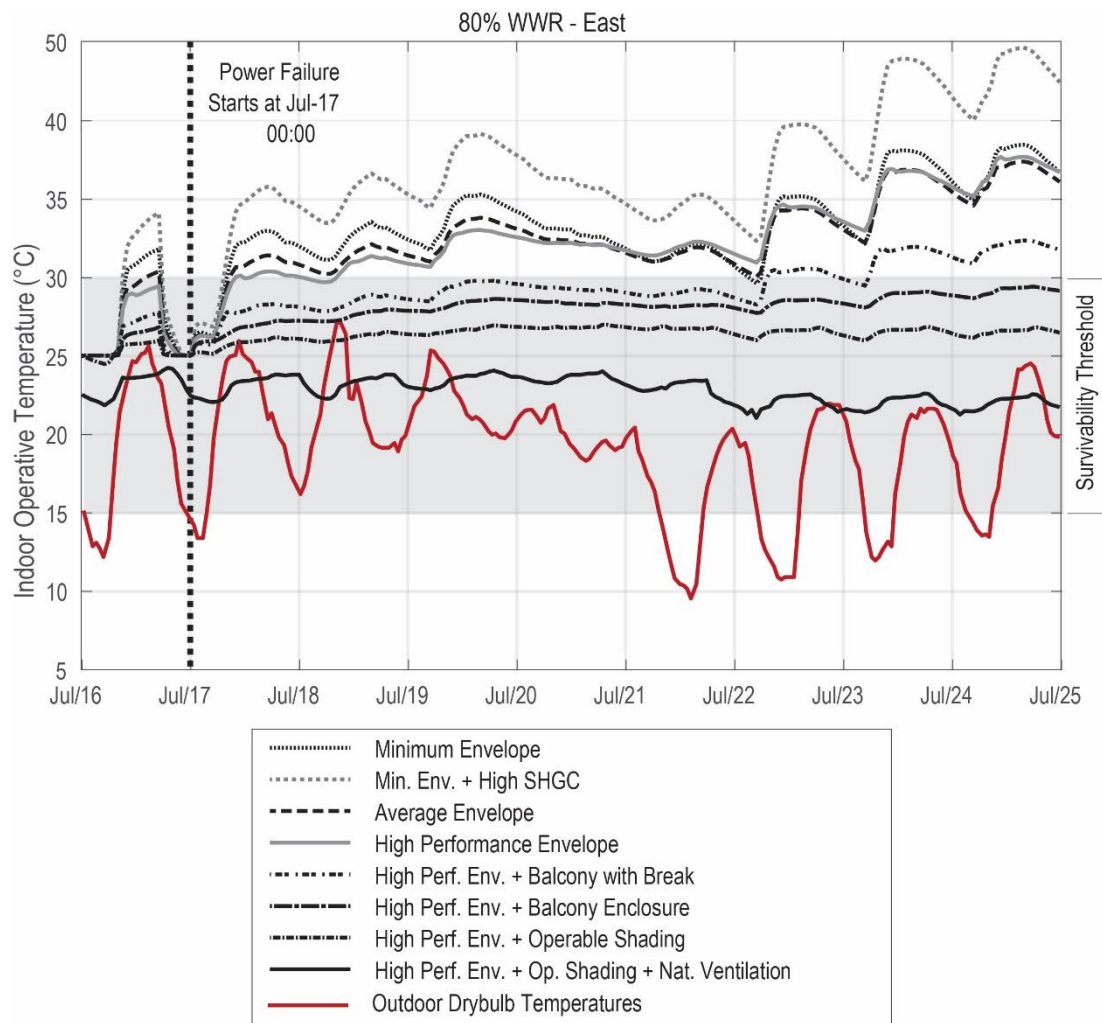


Figure C.8 : Passive survivability performance for an east-facing unit with 80% WWR under summer conditions in Toronto.

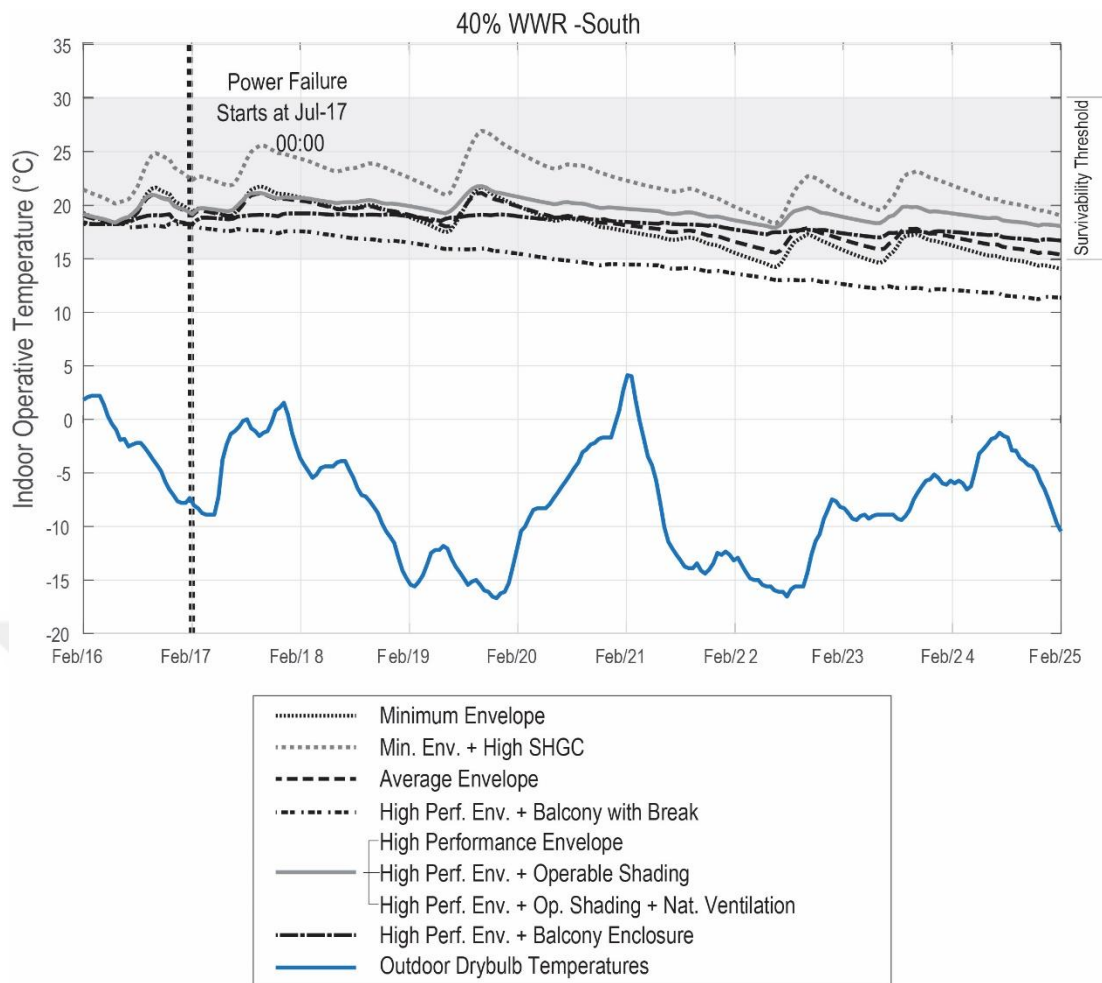


Figure C.9 : Passive survivability performance for a south-facing unit with 40% WWR under winter conditions in Toronto.

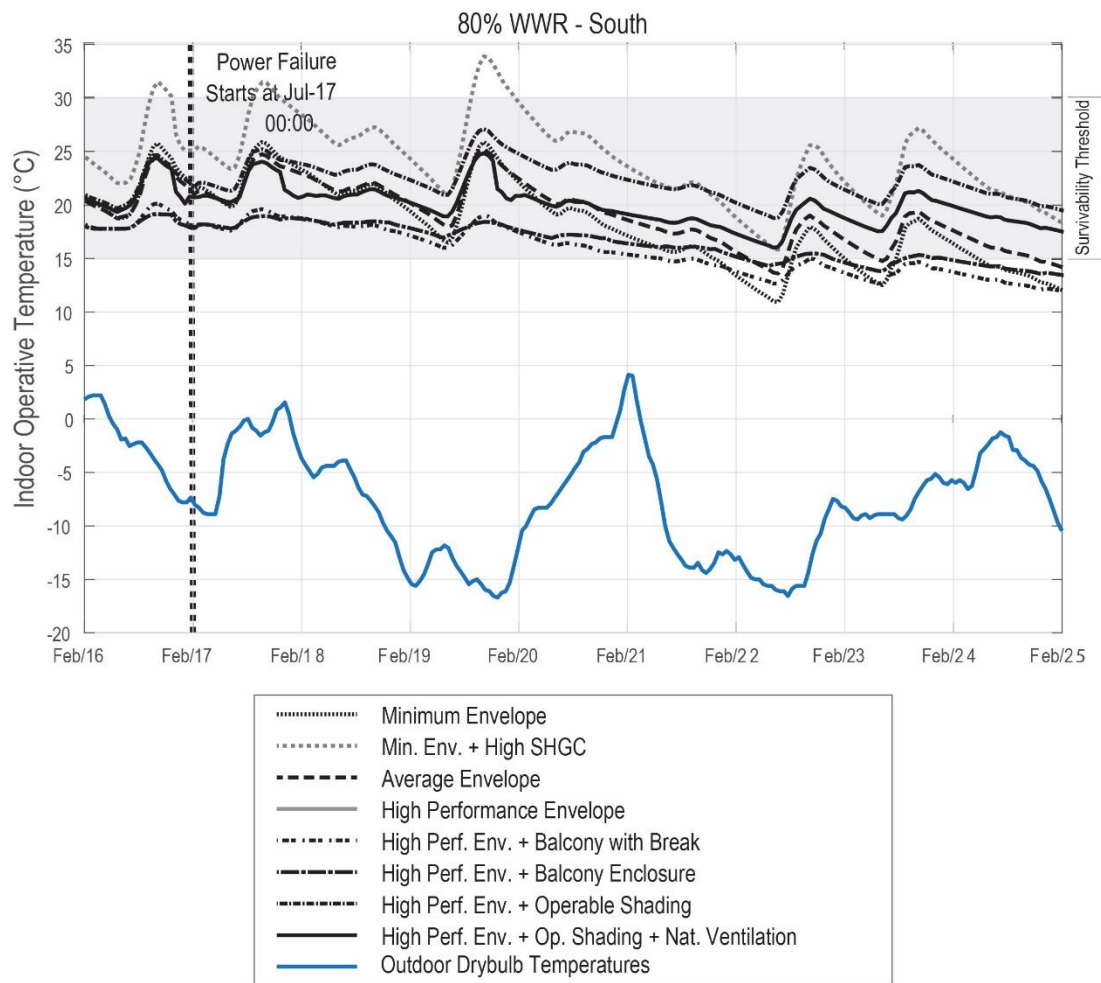


Figure C.10 : Passive survivability performance for a south-facing unit with 80% WWR under winter conditions in Toronto.

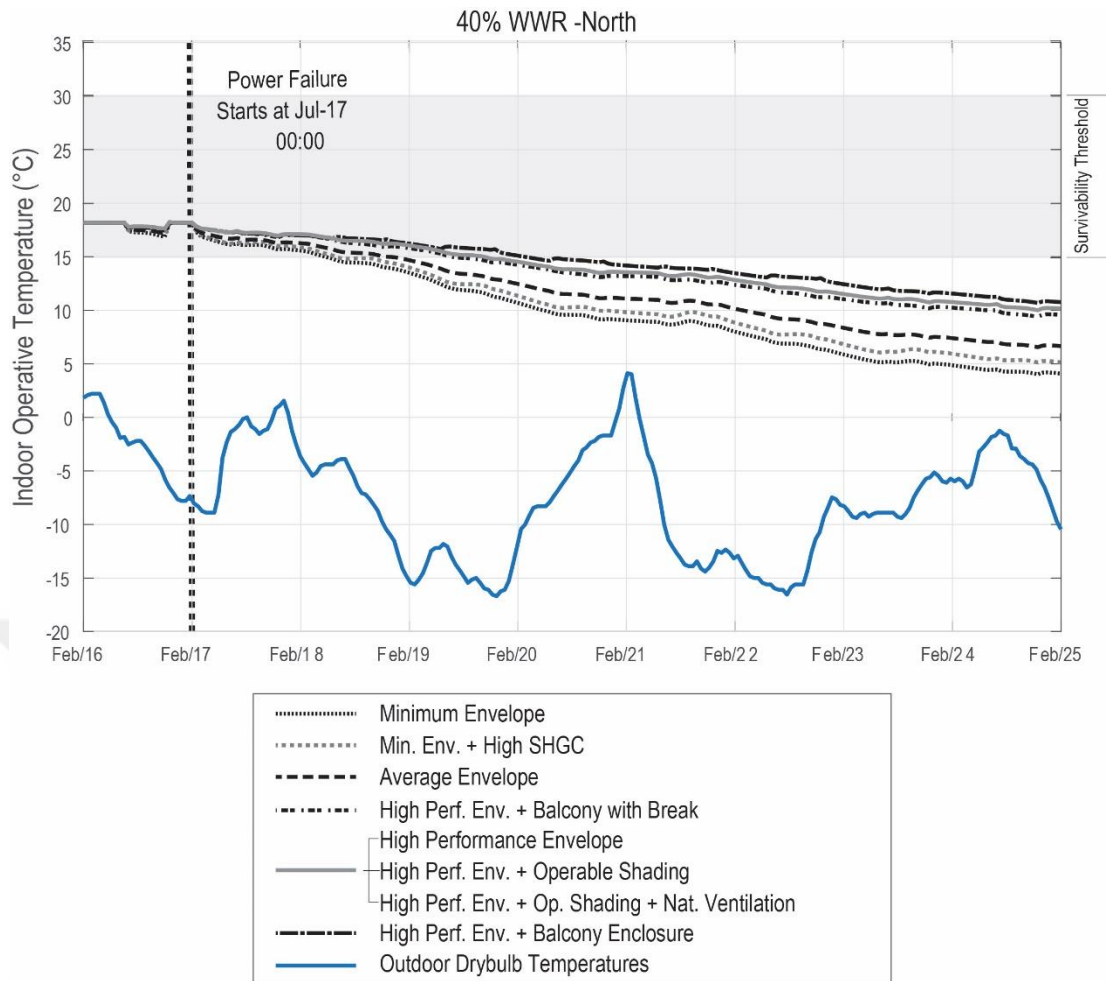


Figure C.11 : Passive survivability performance for a north-facing unit with 40% WWR under winter conditions in Toronto.

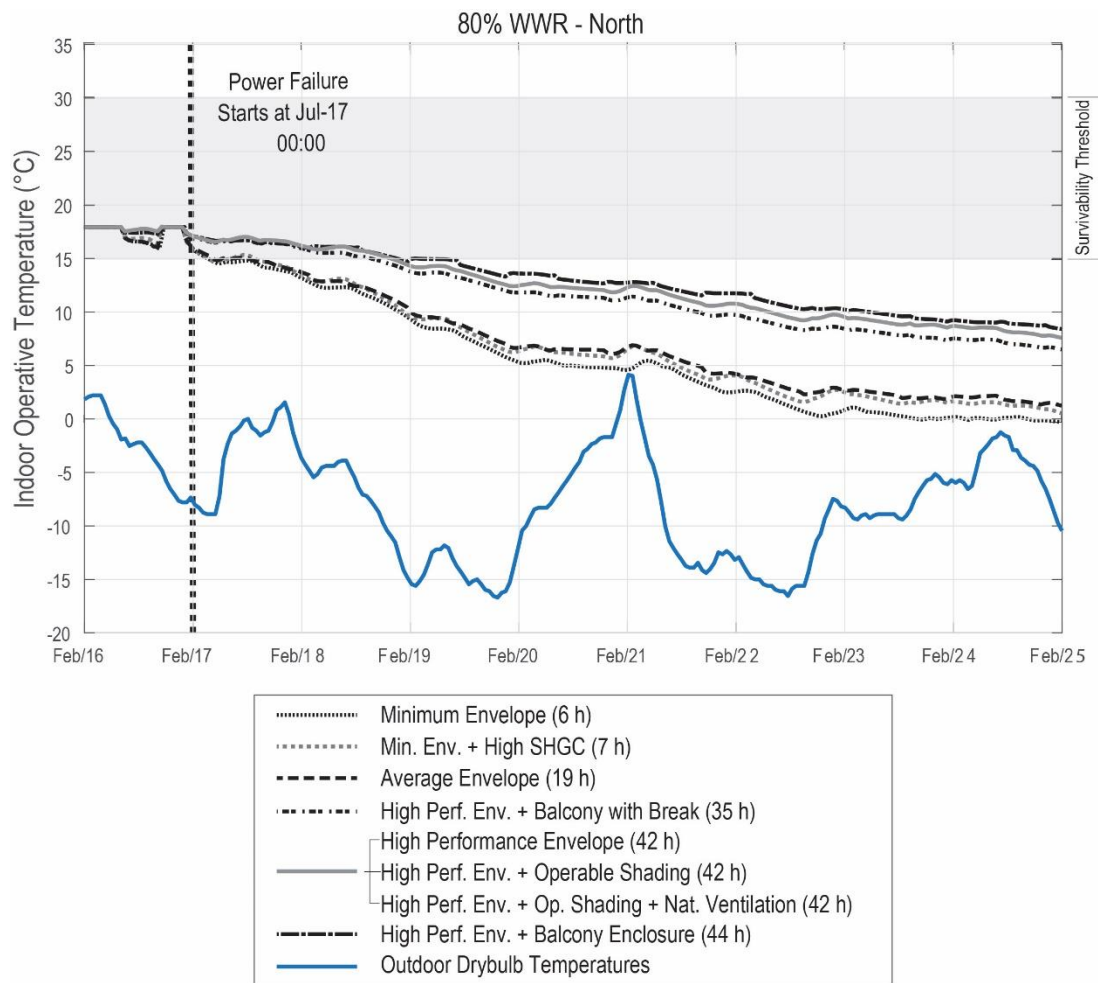


Figure C. 12: Passive survivability performance for a north-facing unit with 80% WWR under winter conditions in Toronto.

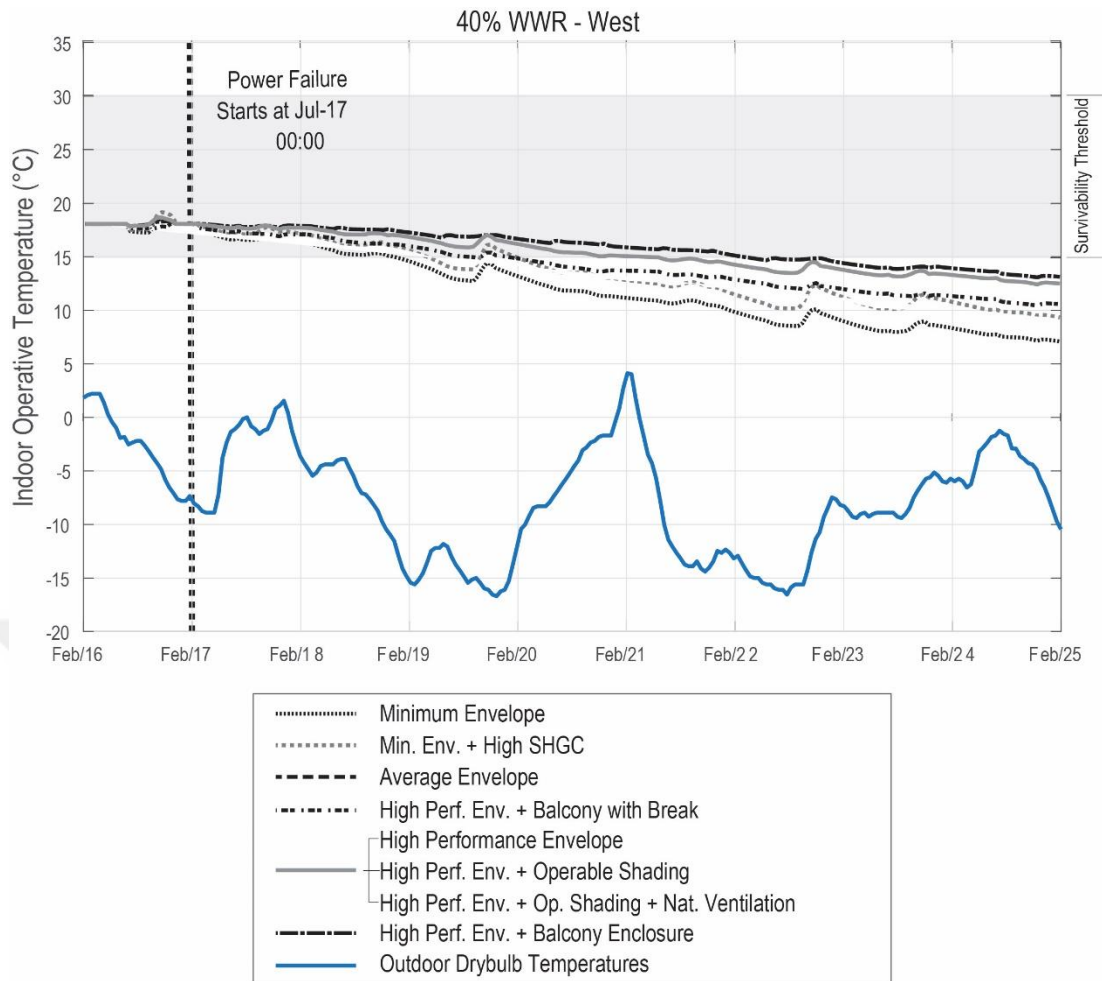


Figure C.13 : Passive survivability performance for a west-facing unit with 40% WWR under winter conditions in Toronto.

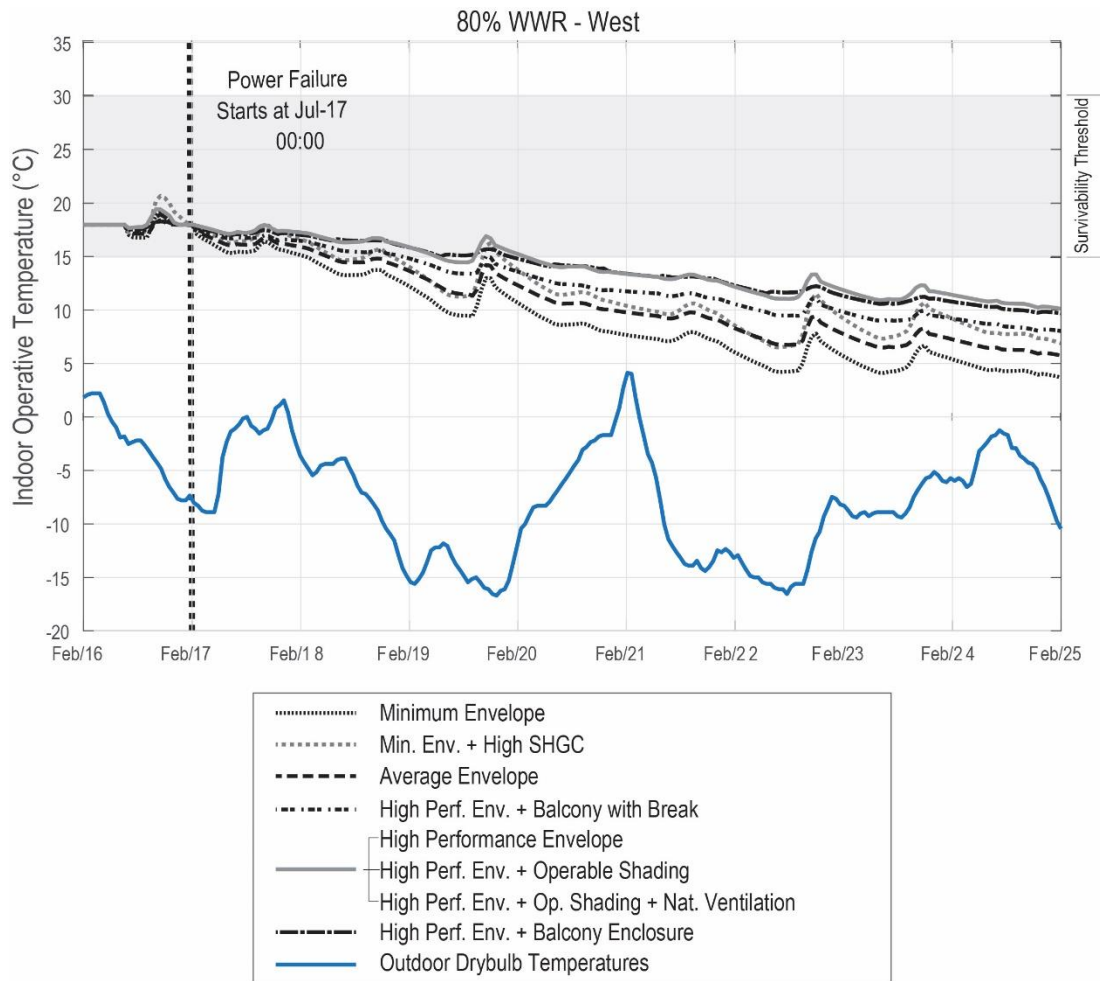


Figure C.14 : Passive survivability performance for a west-facing unit with 80% WWR under winter conditions in Toronto.

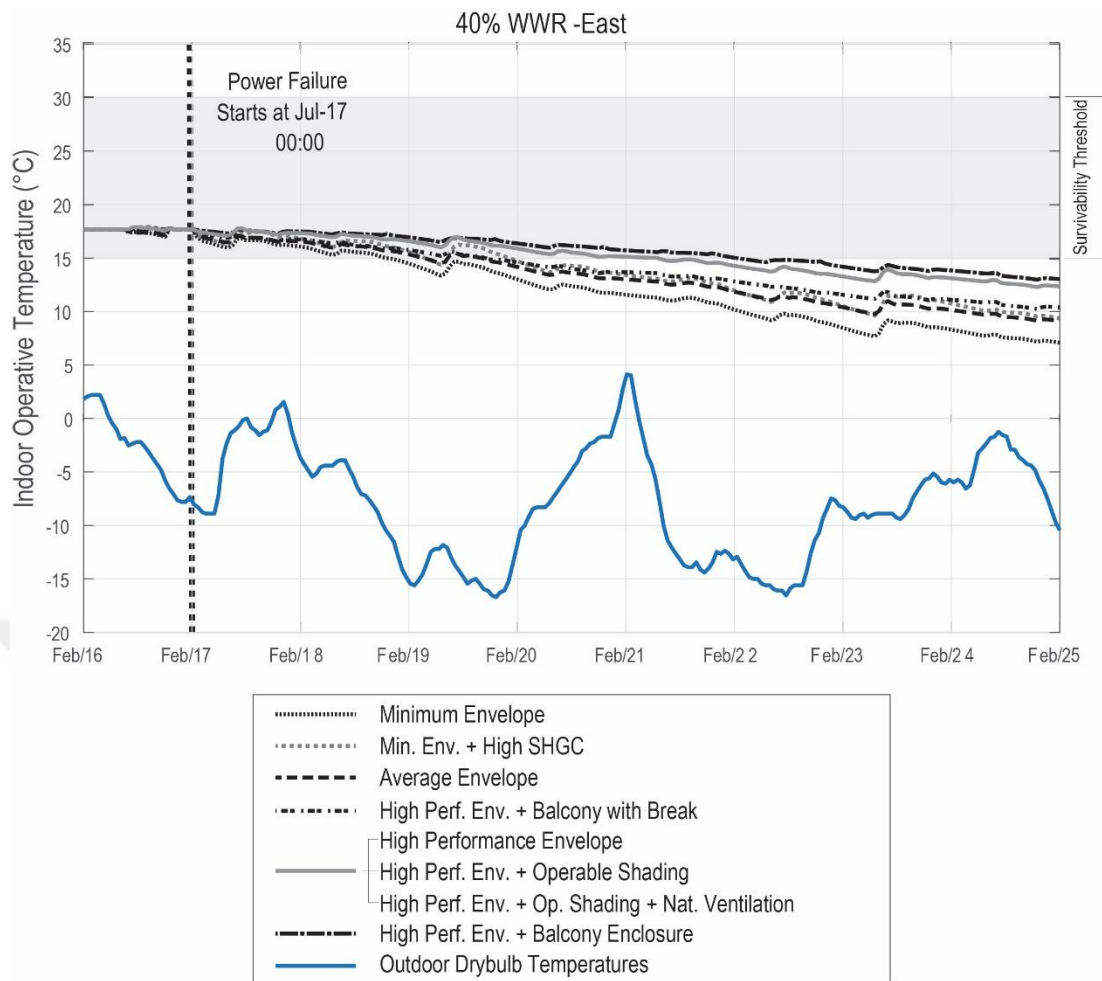


Figure C.15 : Passive survivability performance for an east-facing unit with 40% WWR under winter conditions in Toronto.

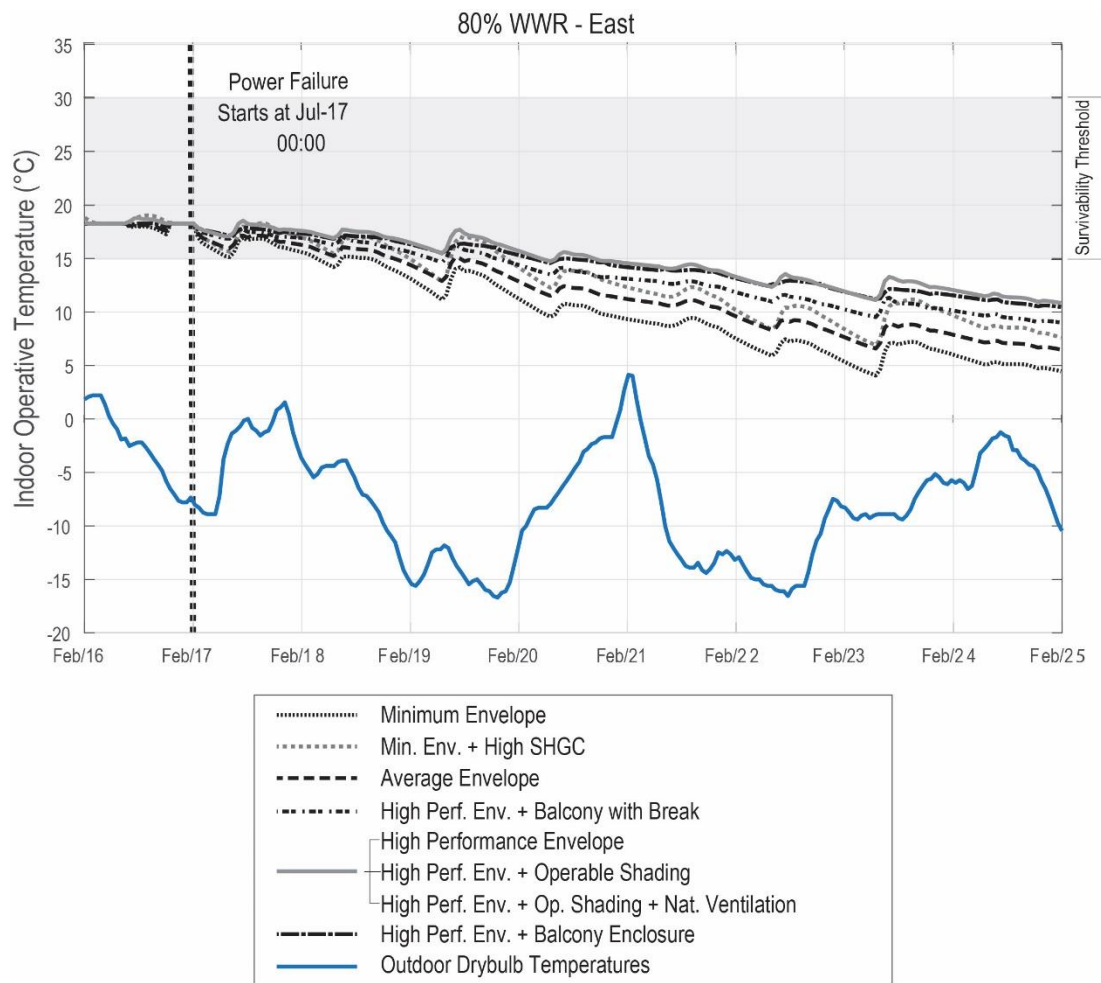


Figure C.16 : Passive survivability performance for an east-facing unit with 80% WWR under winter conditions in Toronto.

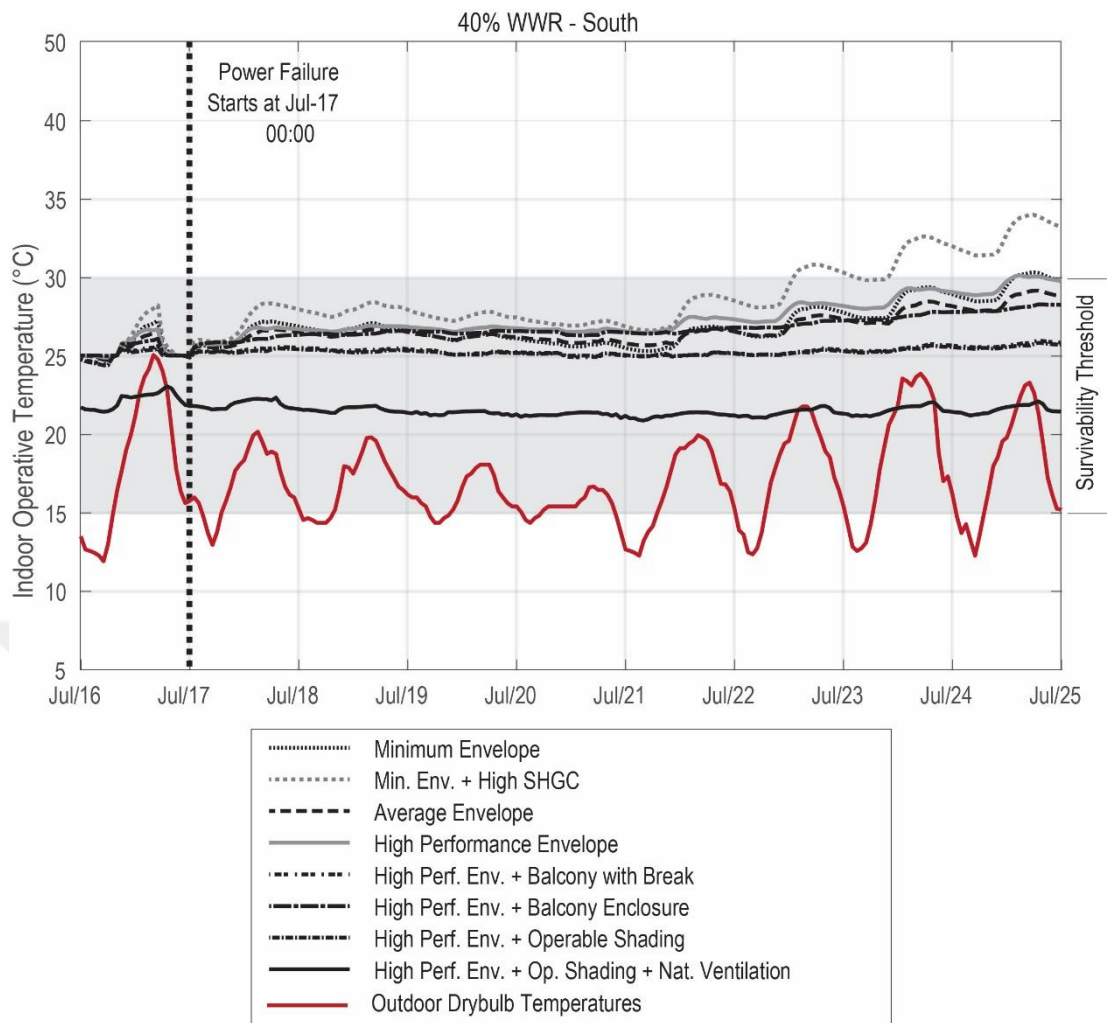


Figure C.17 : Passive survivability performance for a south-facing unit with 40% WWR under summer conditions in Vancouver.

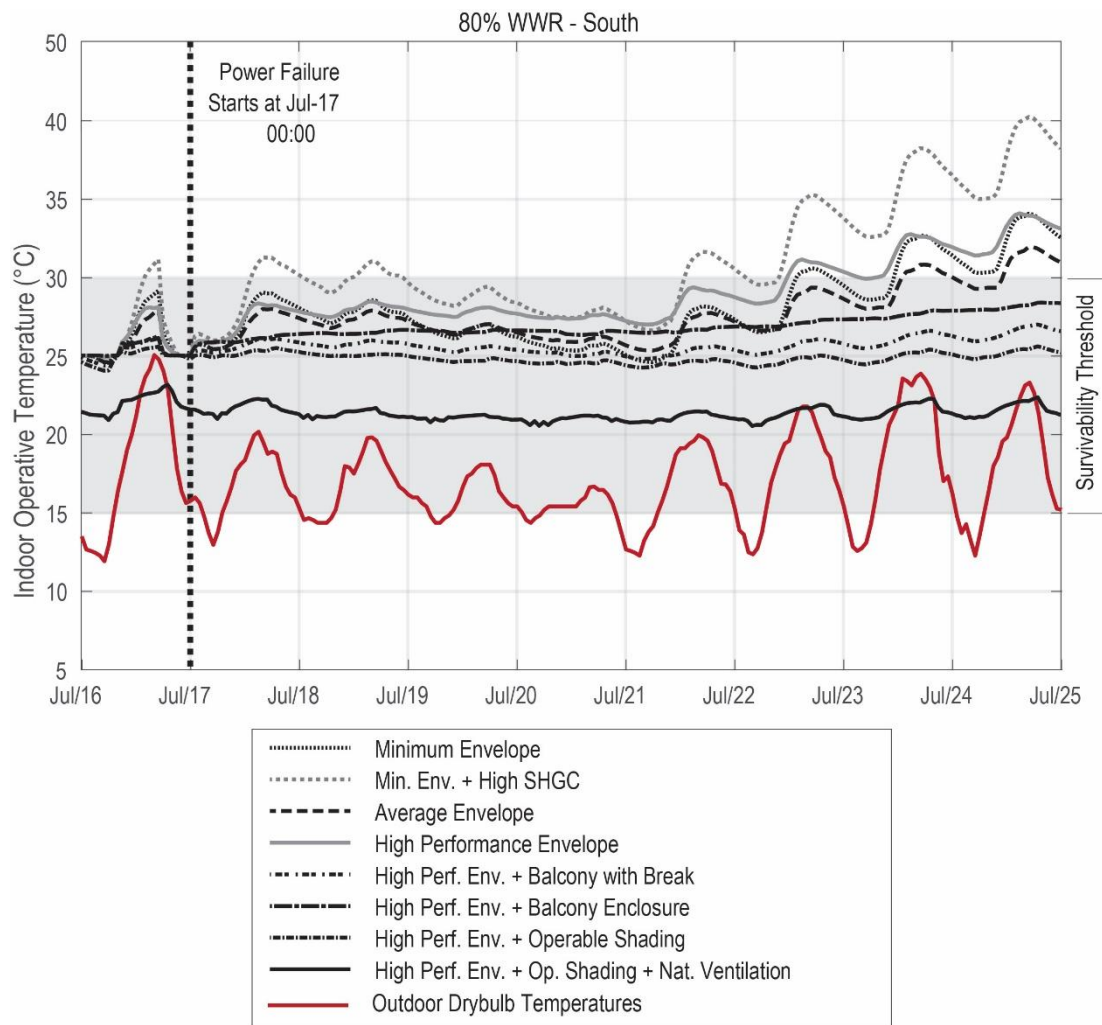


Figure C.18 : Passive survivability performance for a south-facing unit with 80% WWR under summer conditions in Vancouver.

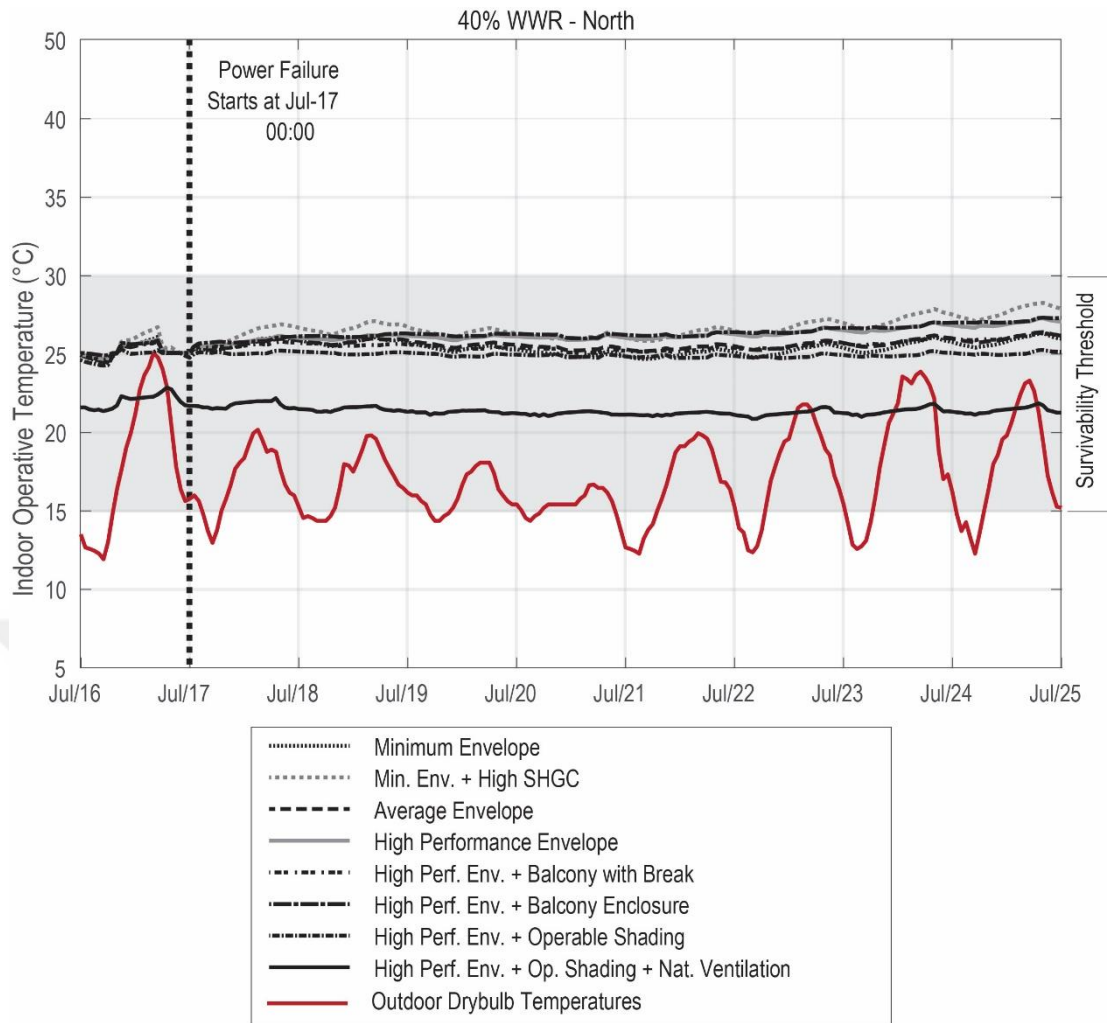


Figure C.19 : Passive survivability performance for a north-facing unit with 40% WWR under summer conditions in Vancouver.

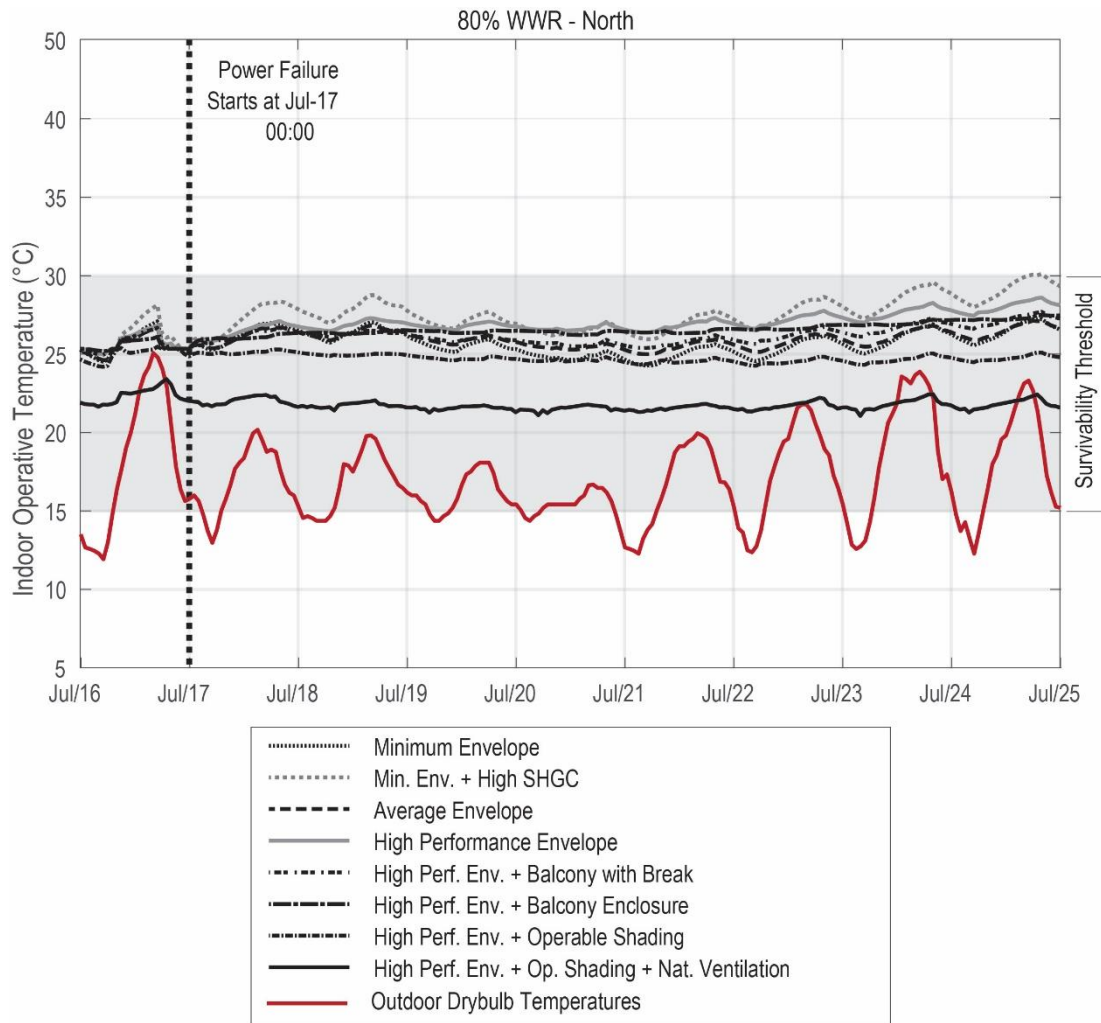


Figure C.20 : Passive survivability performance for a north-facing unit with 80% WWR under summer conditions in Vancouver.

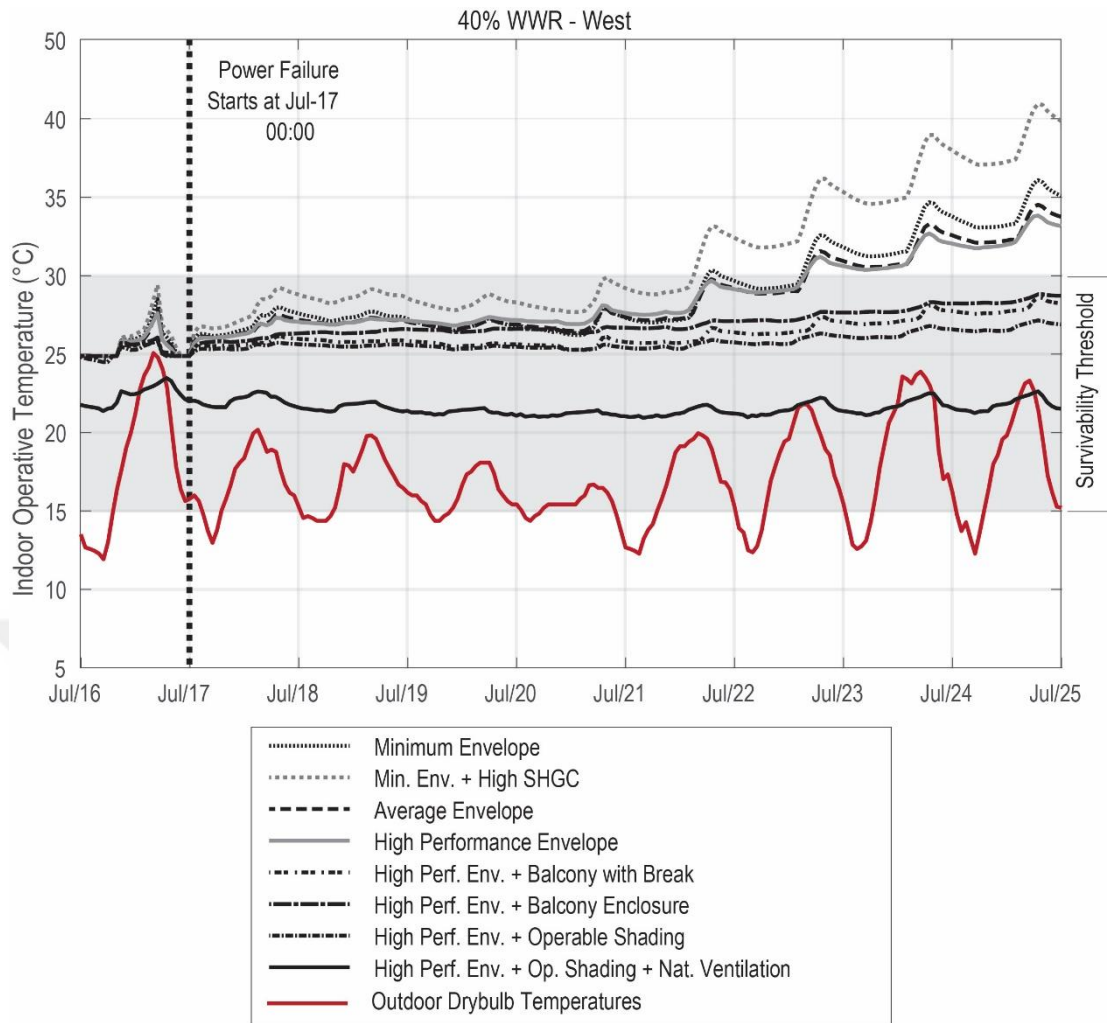


Figure C.21 : Passive survivability performance for a west-facing unit with 40% WWR under summer conditions in Vancouver.

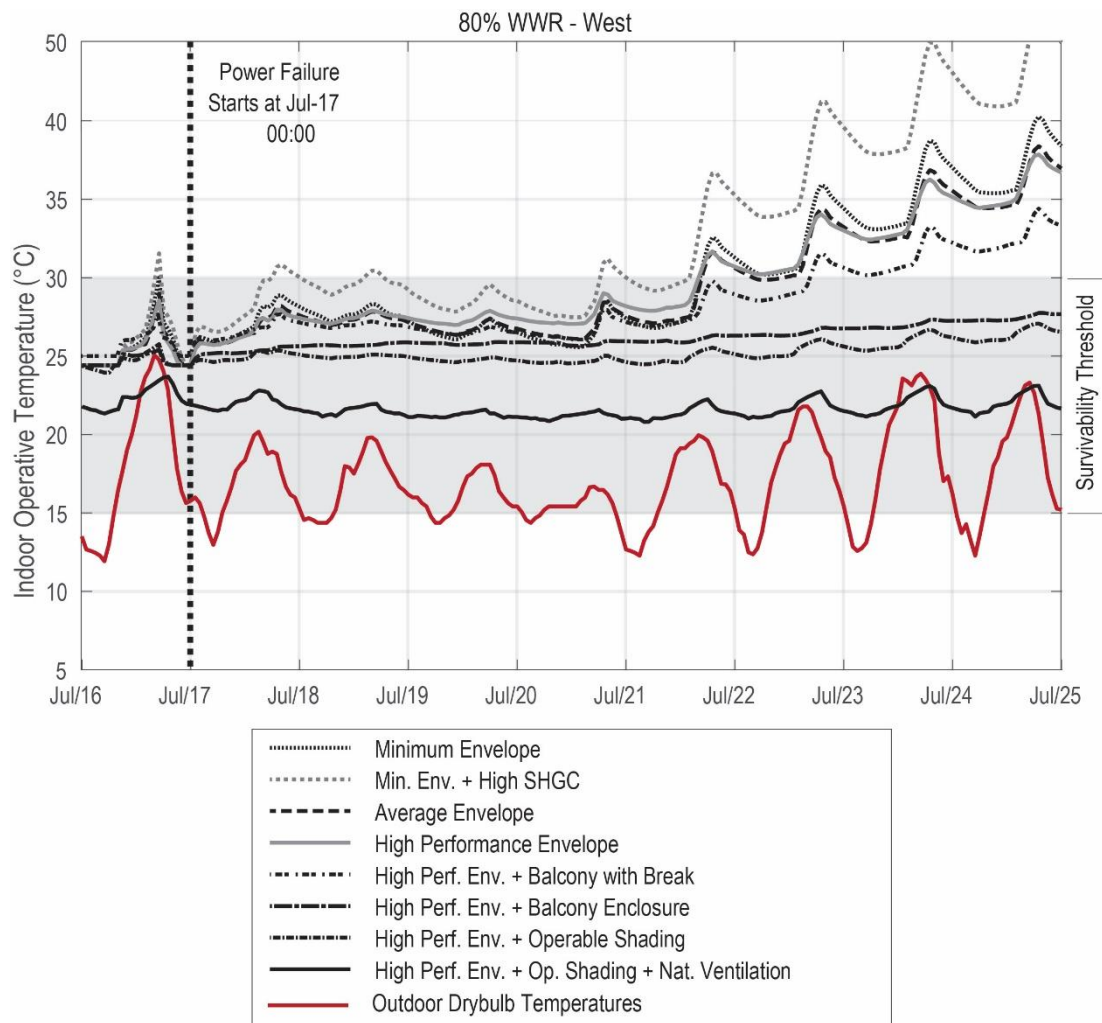


Figure C.22 : Passive survivability performance for a west-facing unit with 80% WWR under summer conditions in Vancouver.

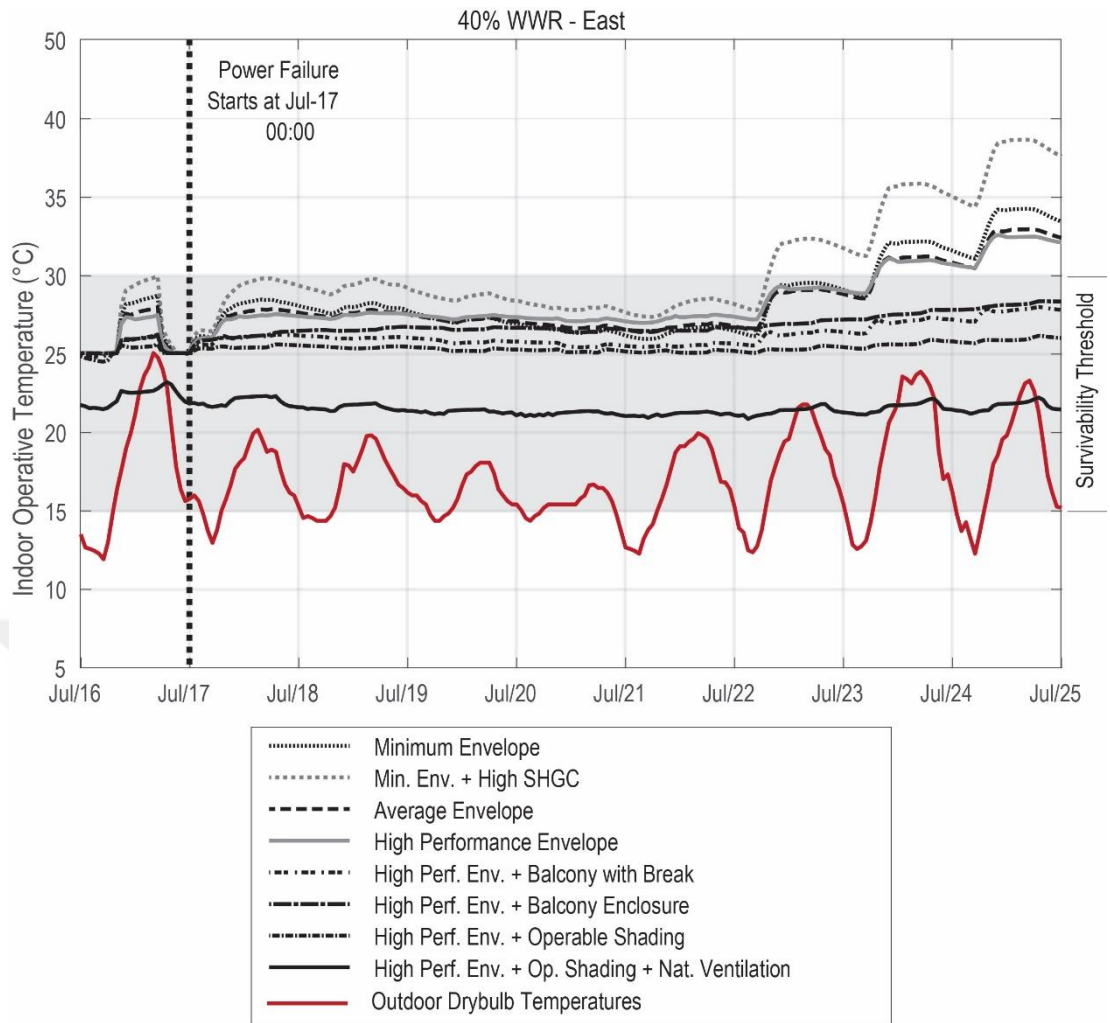


Figure C.23 : Passive survivability performance for an east-facing unit with 40% WWR under summer conditions in Vancouver.

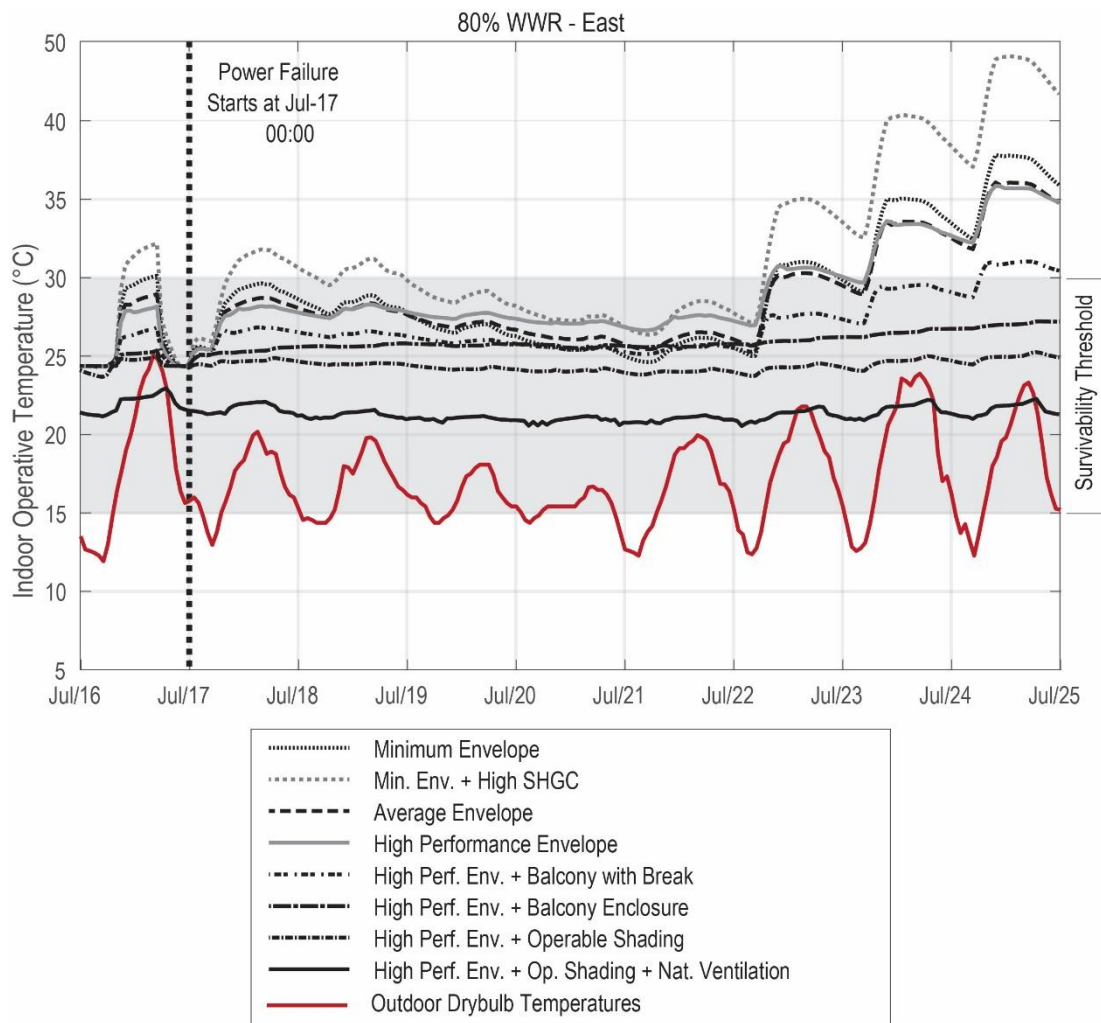


Figure C.24 : Passive survivability performance for an east-facing unit with 80% WWR under summer conditions in Vancouver.

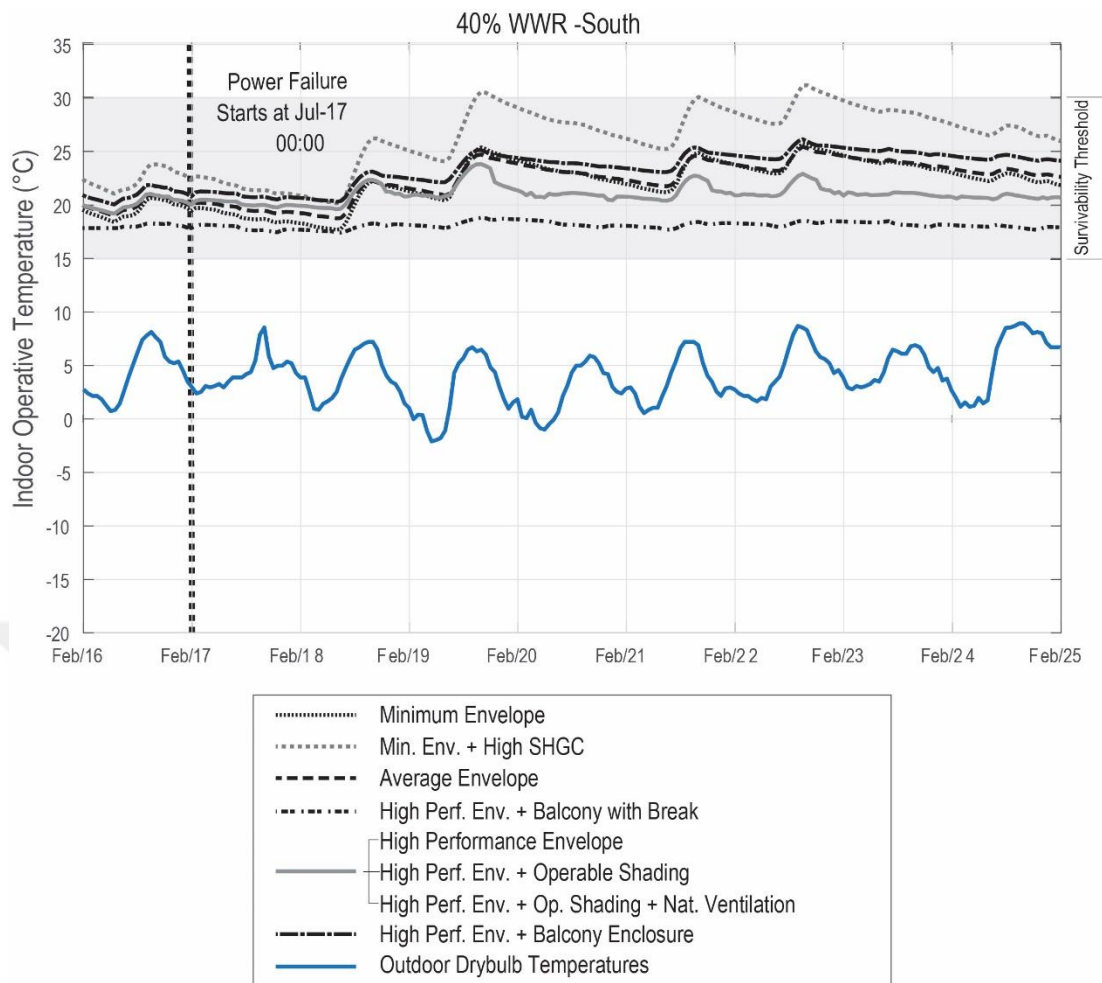


Figure C.25 : Passive survivability performance for a south-facing unit with 40% WWR under winter conditions in Vancouver.

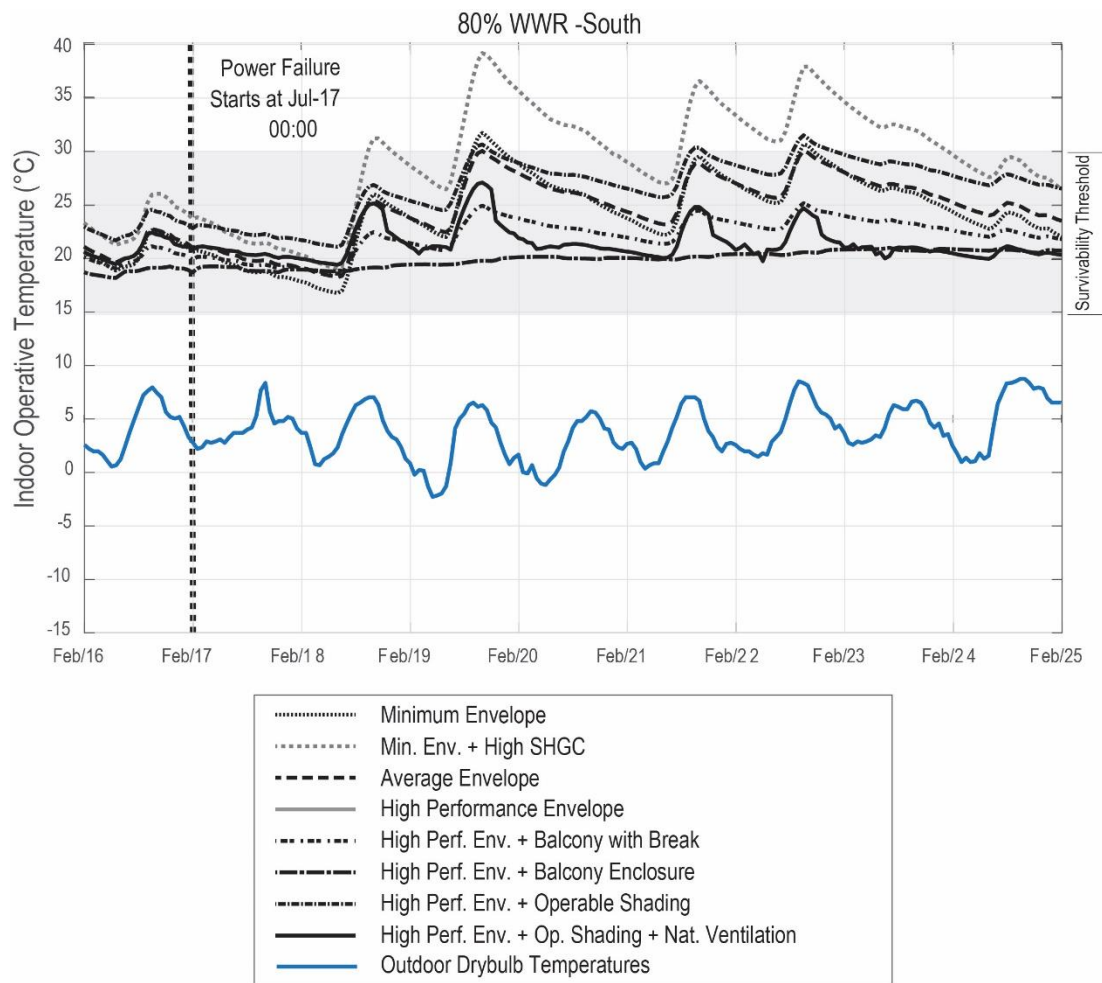


Figure C.26 : Passive survivability performance for a south-facing unit with 80% WWR under winter conditions in Vancouver.

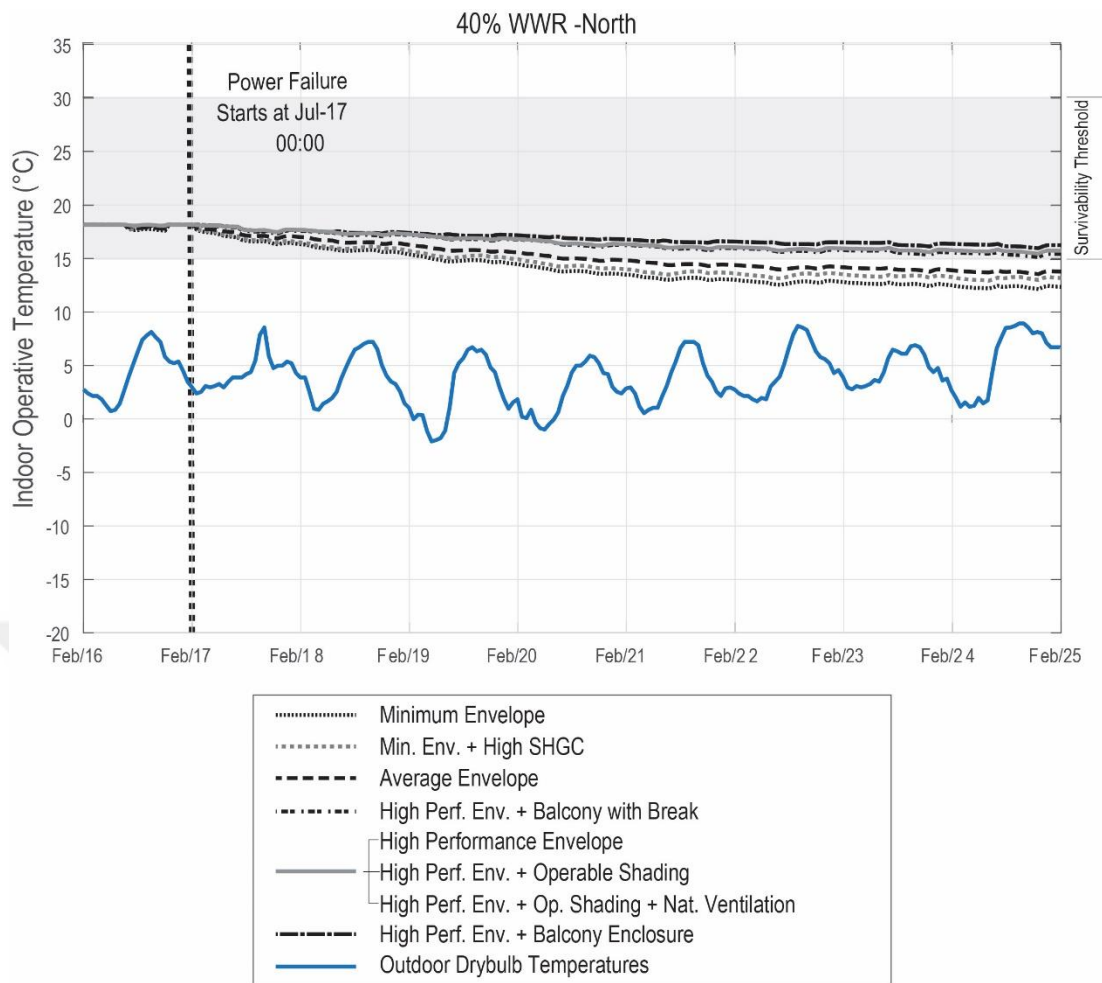


Figure C.27 : Passive survivability performance for a north-facing unit with 40% WWR under winter conditions in Vancouver.

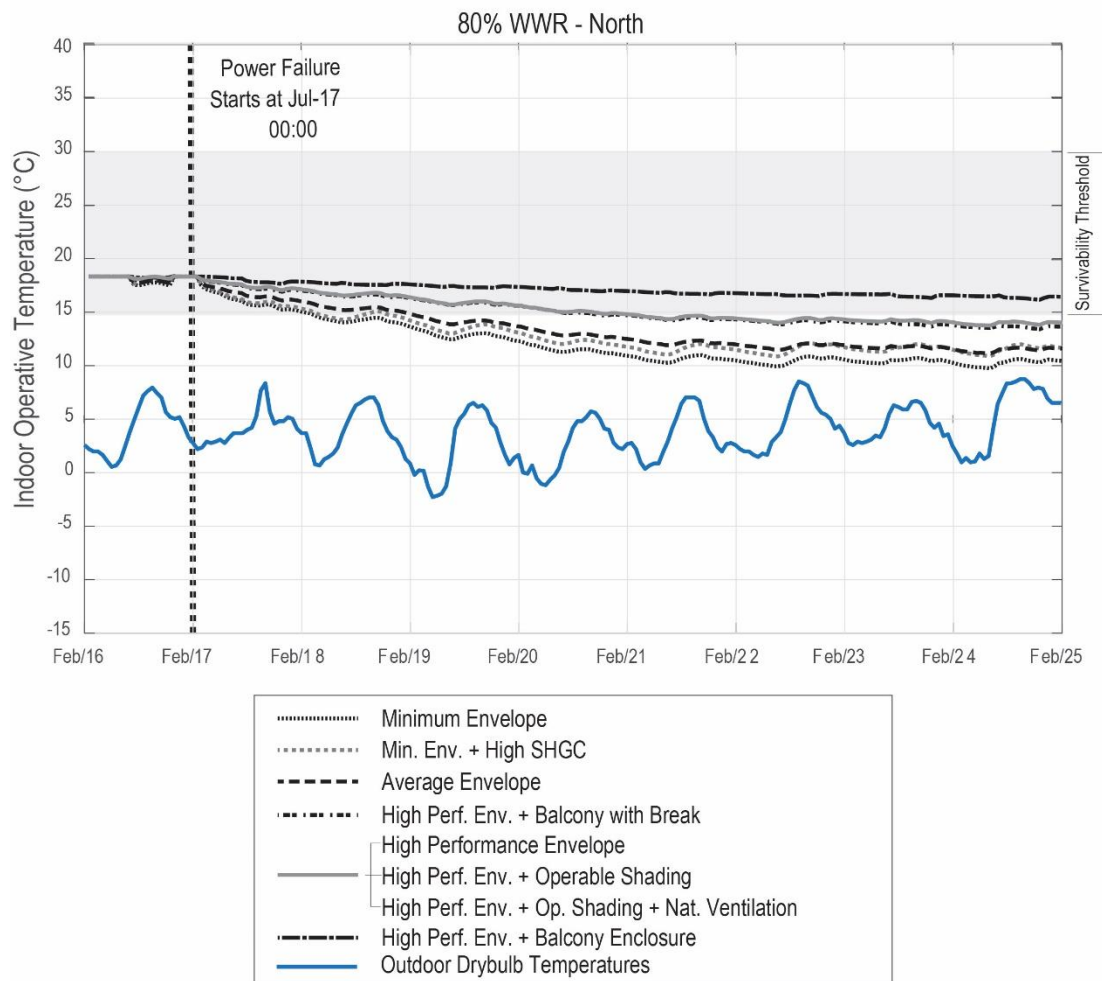


Figure C.28 : Passive survivability performance for a north-facing unit with 80% WWR under winter conditions in Vancouver.

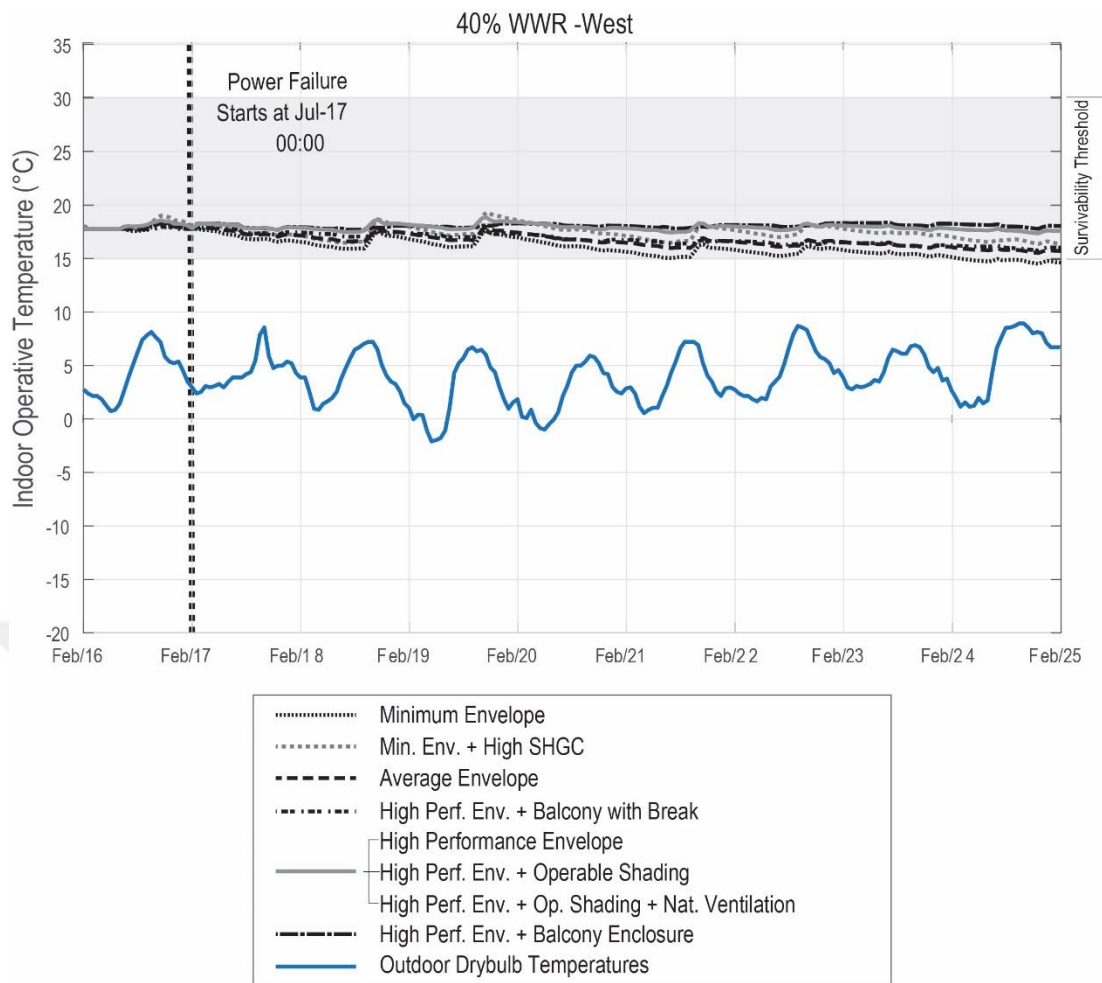


Figure C.29 : Passive survivability performance for a west-facing unit with 40% WWR under winter conditions in Vancouver.

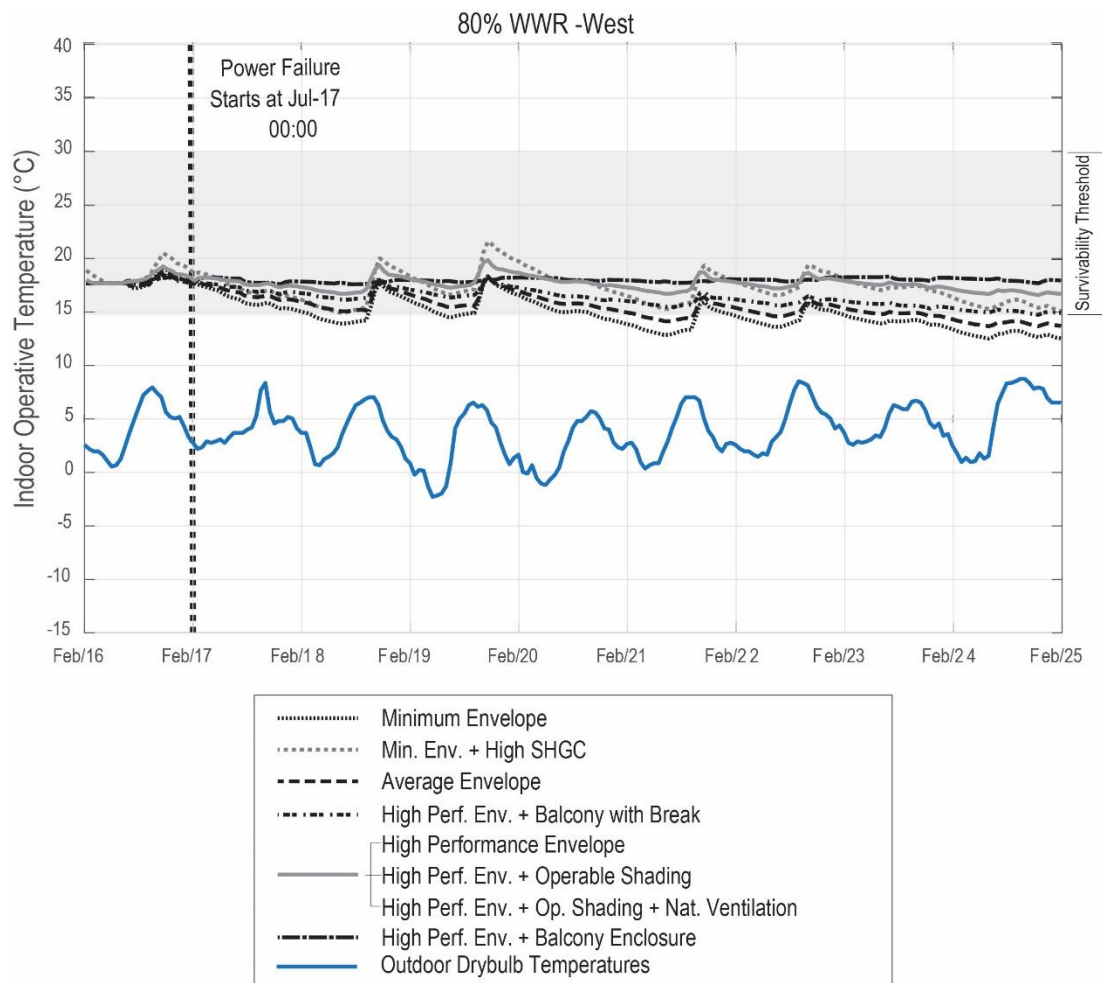


Figure C.30 : Passive survivability performance for a west-facing unit with 80% WWR under winter conditions in Vancouver.

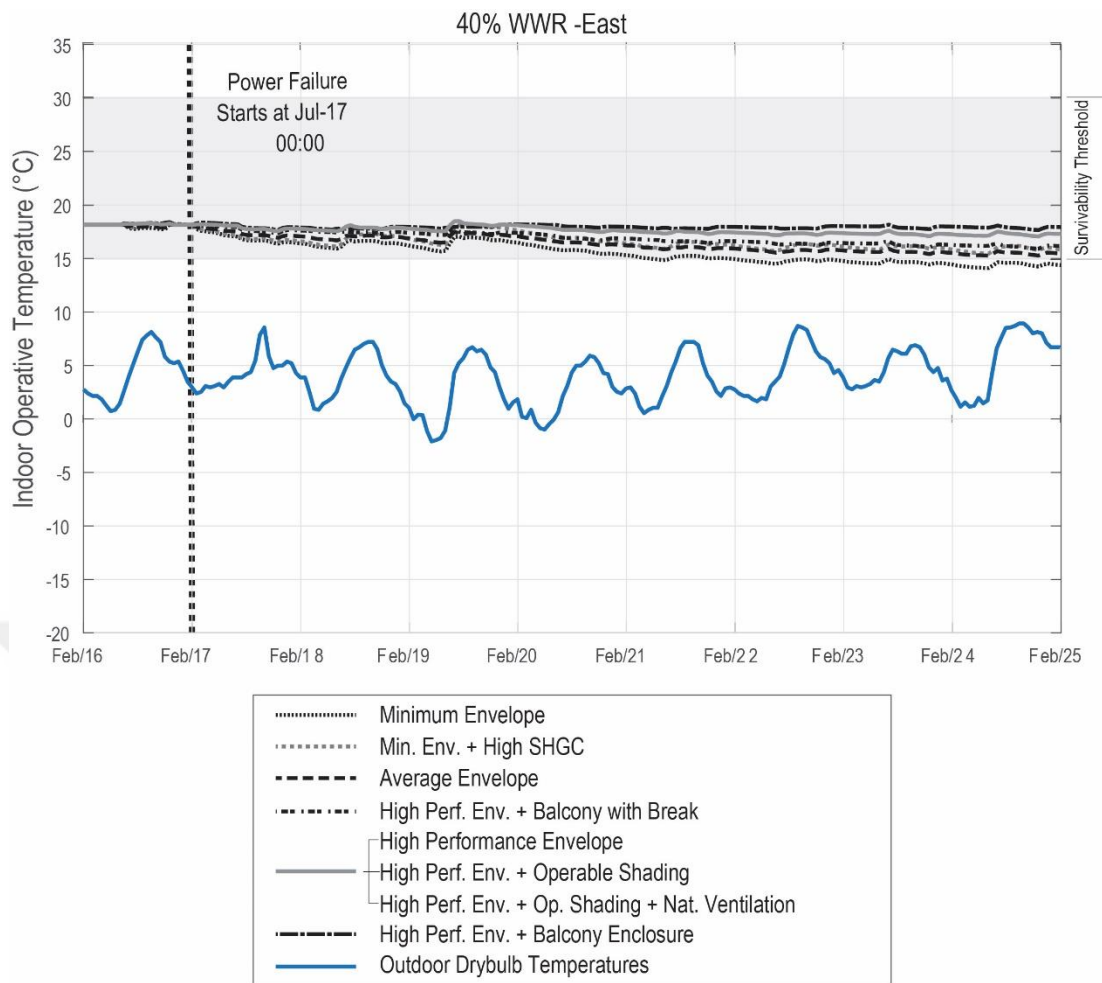


Figure C.31 : Passive survivability performance for an east-facing unit with 40% WWR under winter conditions in Vancouver.

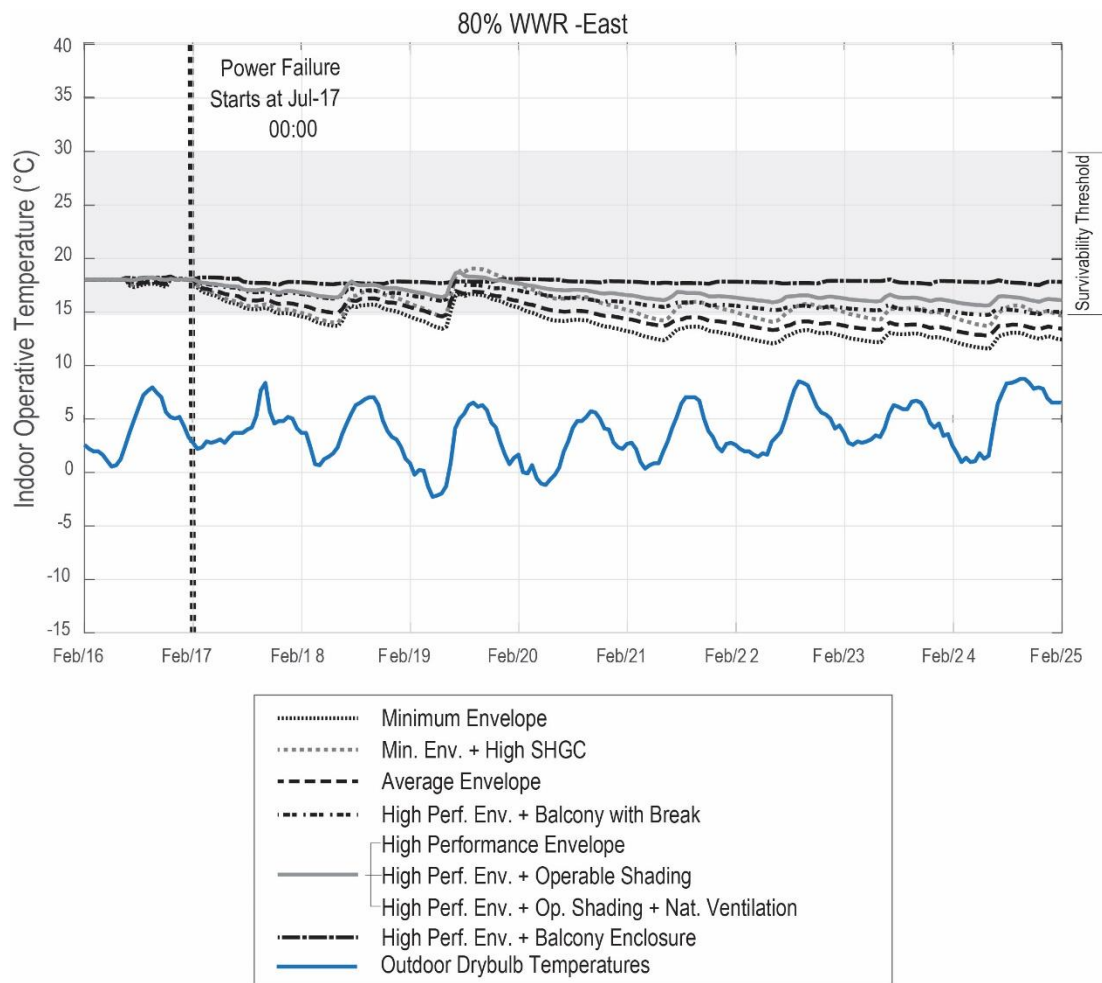


Figure C.32 : Passive survivability performance for an east-facing unit with 80% WWR under winter conditions in Vancouver.

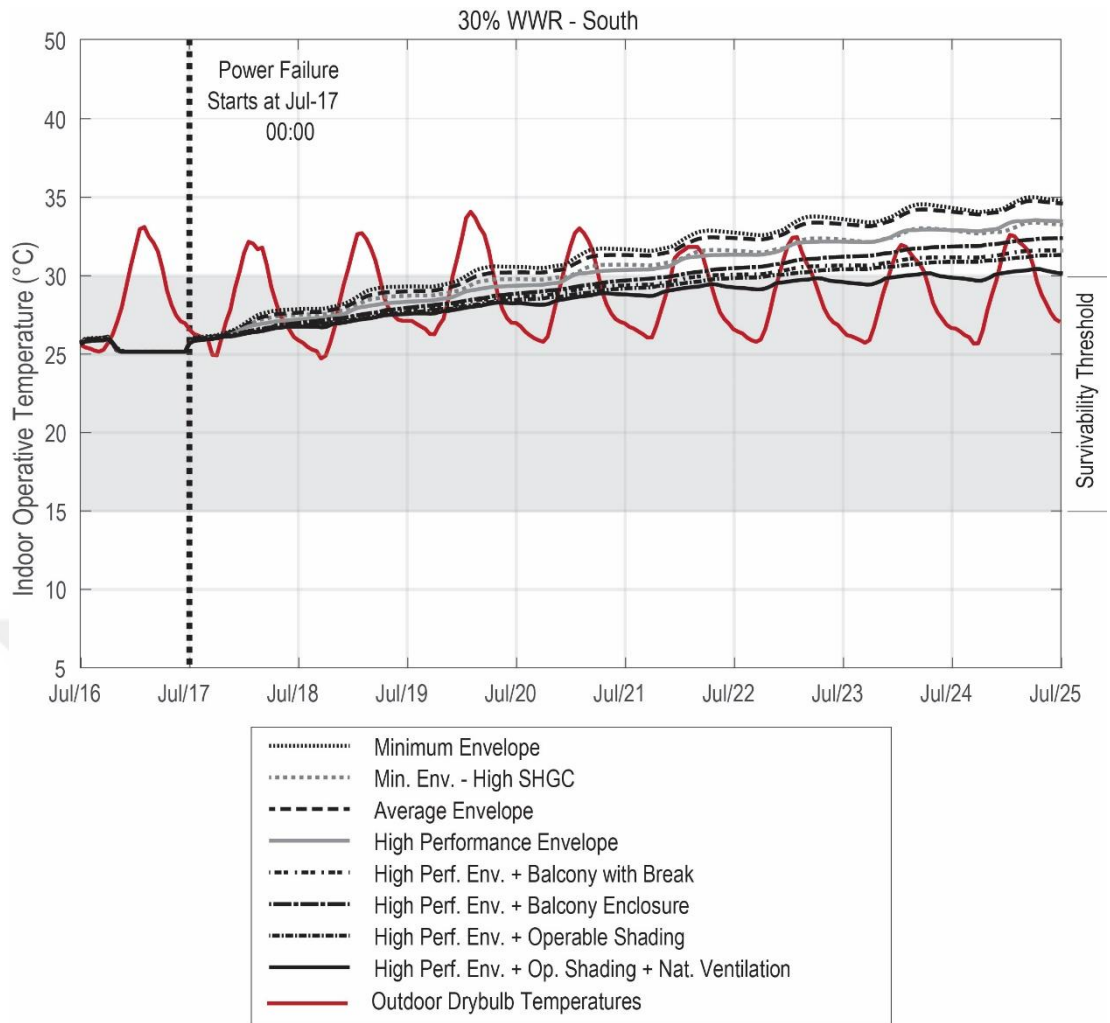


Figure C.33 : Passive survivability performance for a south-facing unit with 30% WWR under summer conditions in Adana.

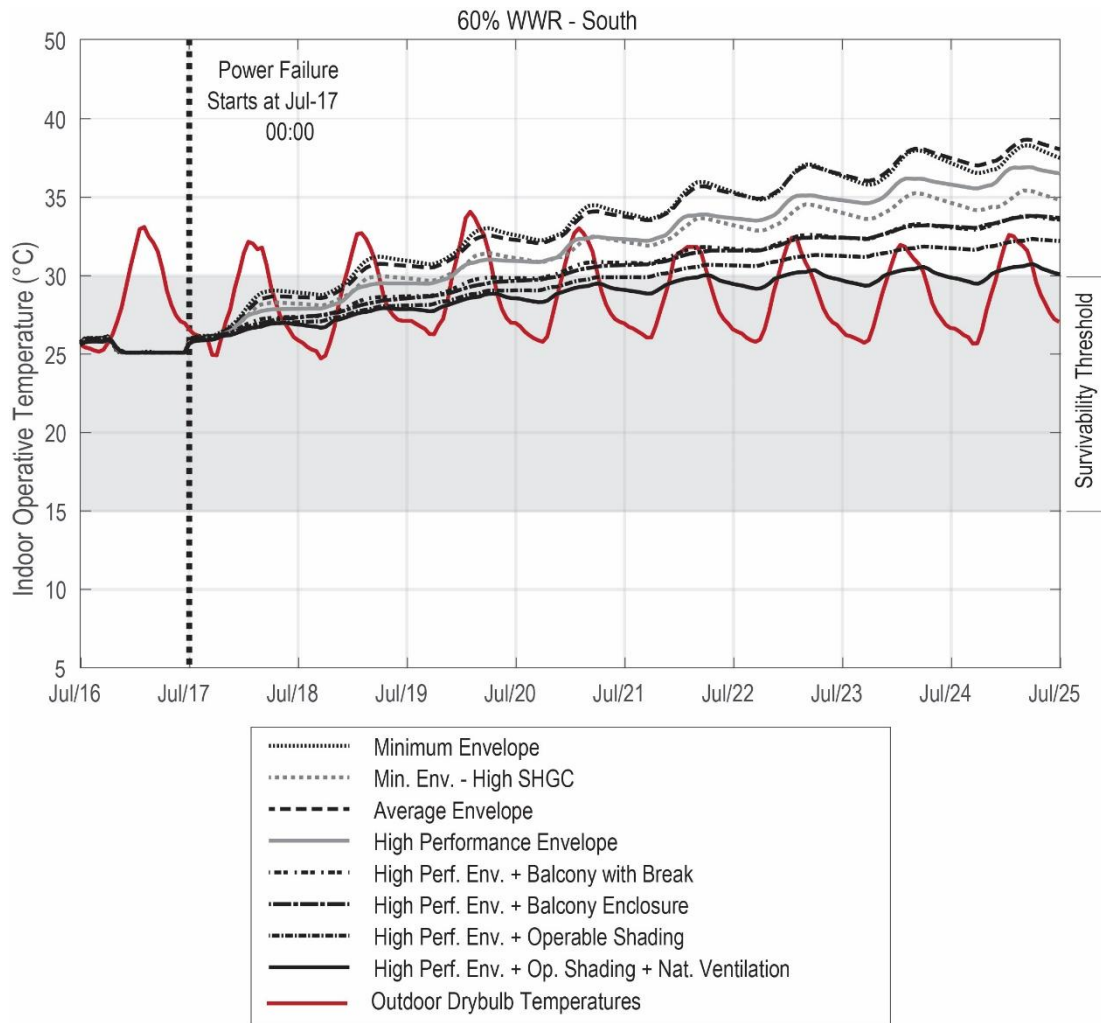


Figure C.34 : Passive survivability performance for a south-facing unit with 60% WWR under summer conditions in Adana.

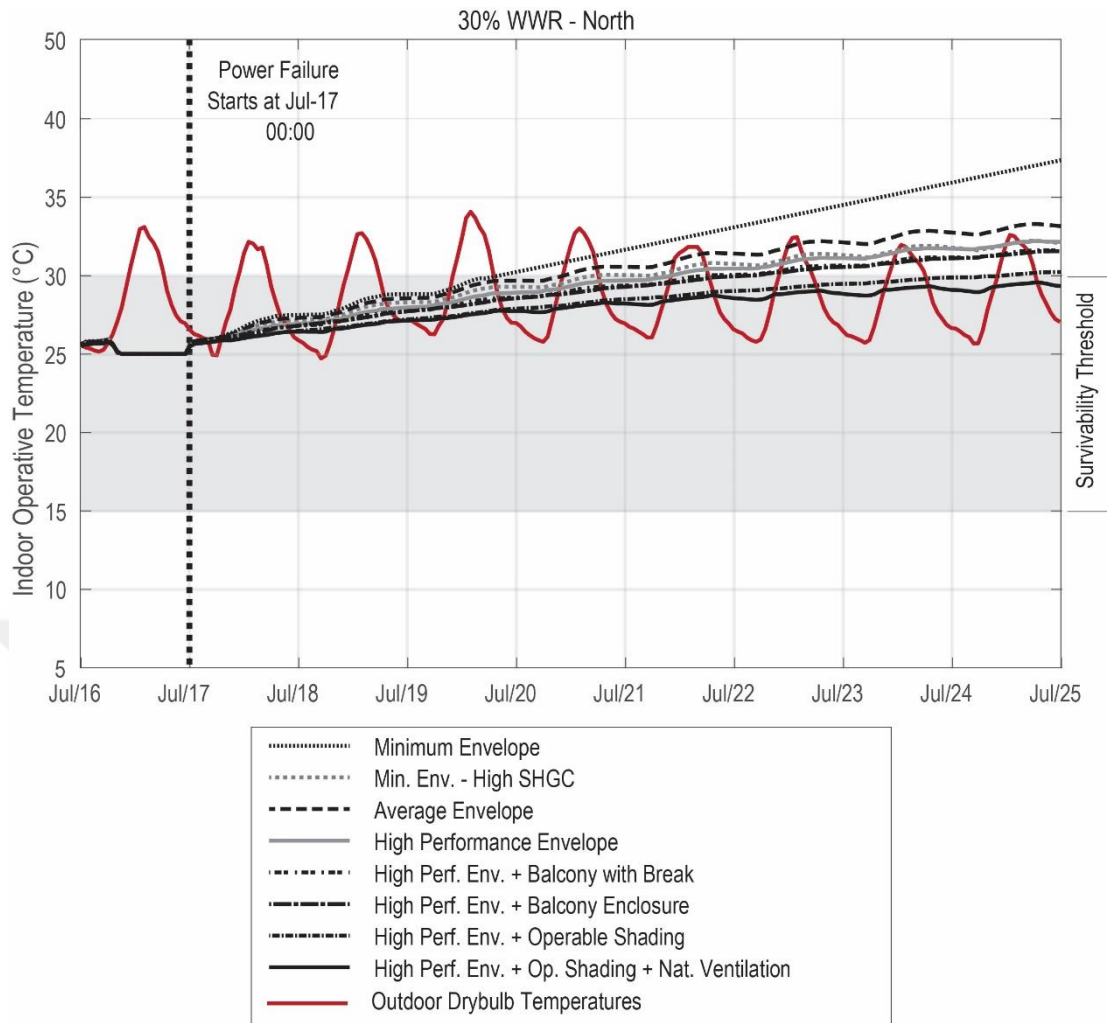


Figure C.35 : Passive survivability performance for a north-facing unit with 30% WWR under summer conditions in Adana.

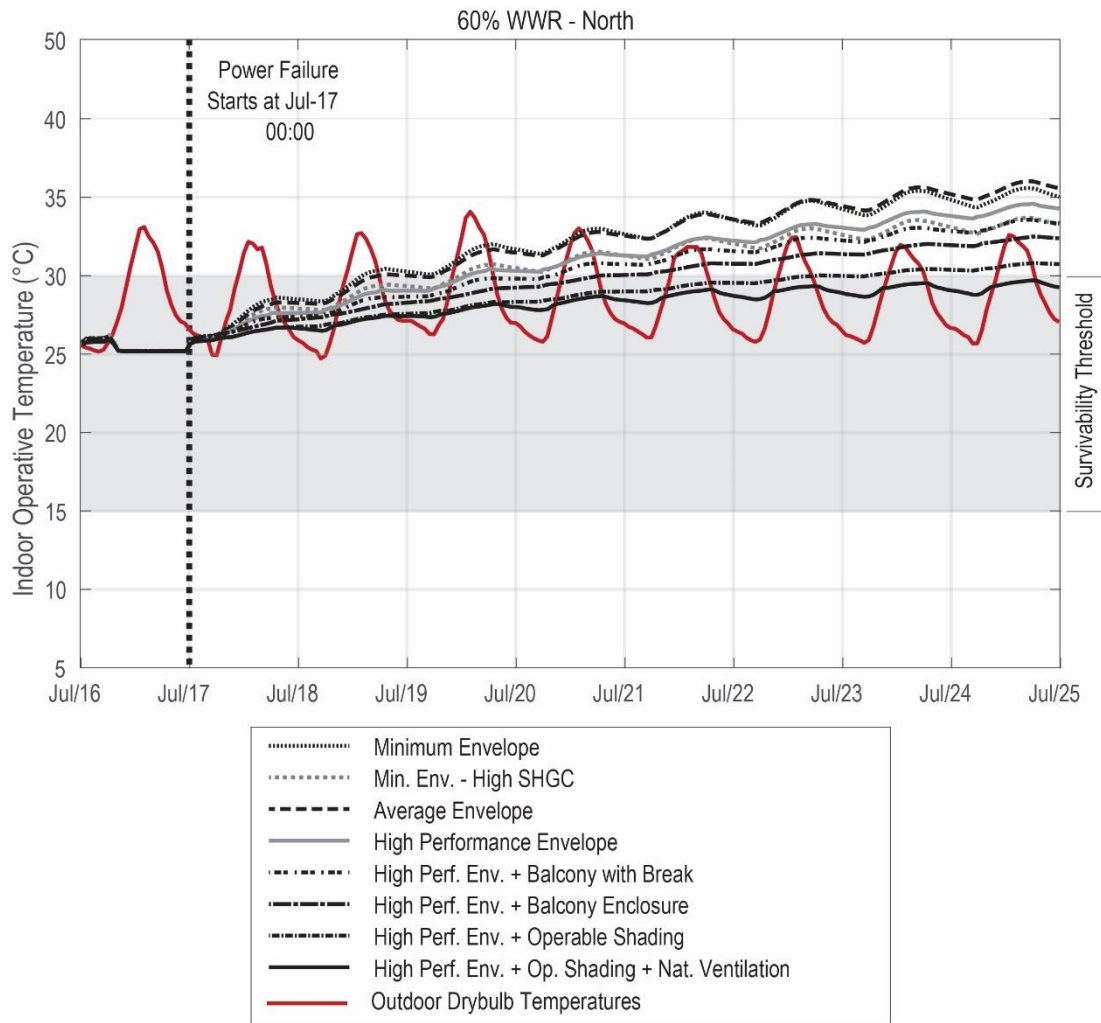


Figure C.36 : Passive survivability performance for a north-facing unit with 60% WWR under summer conditions in Adana.

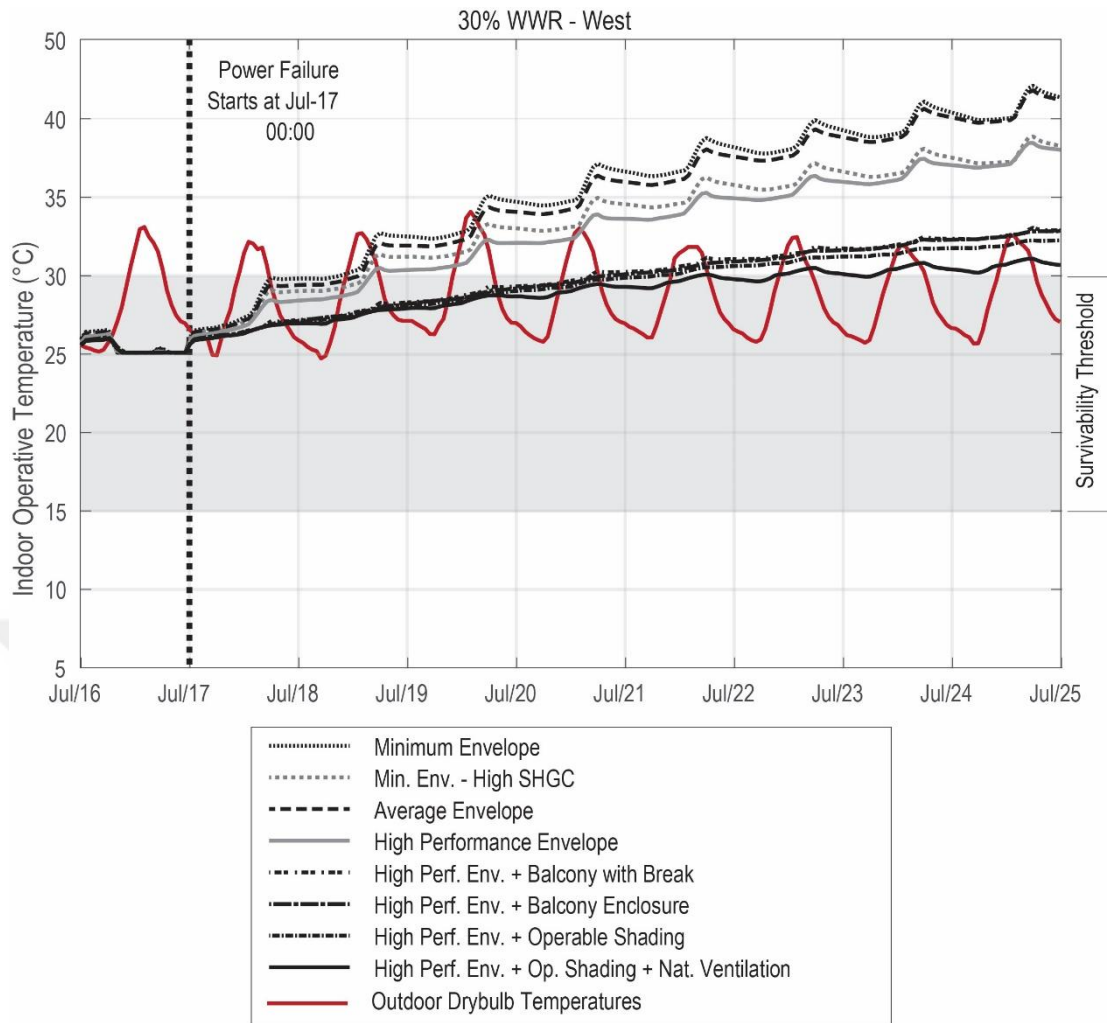


Figure C.37 : Passive survivability performance for a west-facing unit with 30% WWR under summer conditions in Adana.

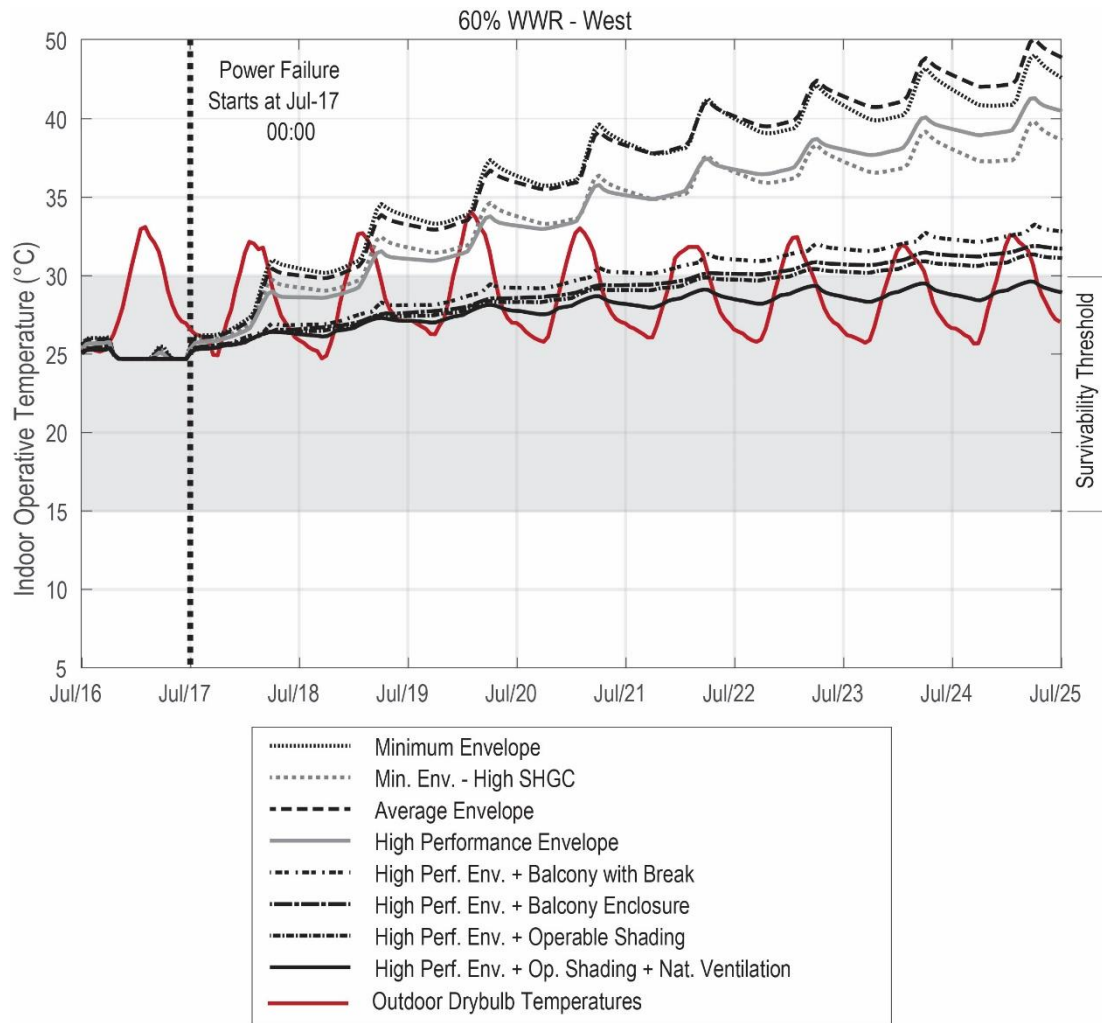


Figure C.38 : Passive survivability performance for a west-facing unit with 60% WWR under summer conditions in Adana.

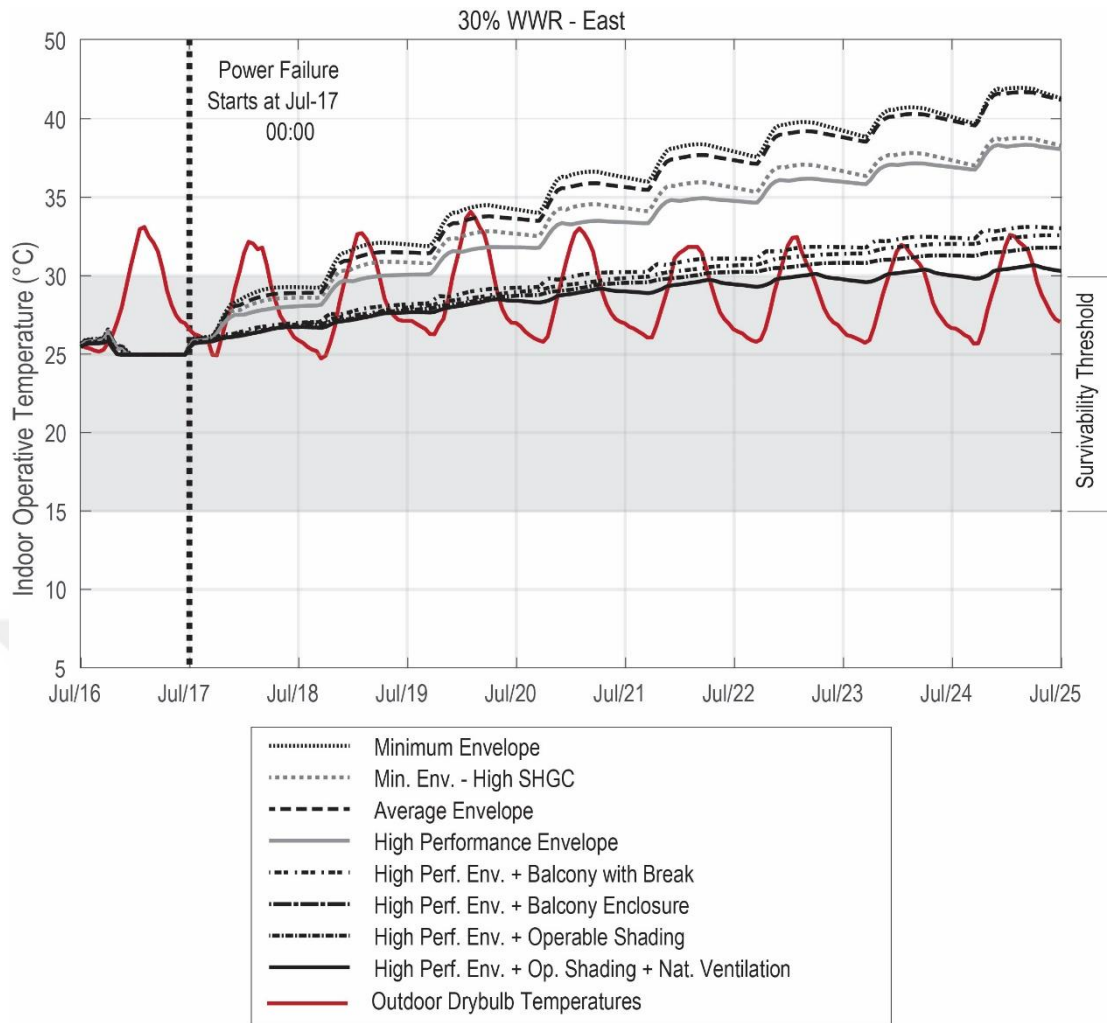


Figure C.39 : Passive survivability performance for an east-facing unit with 30% WWR under summer conditions in Adana.

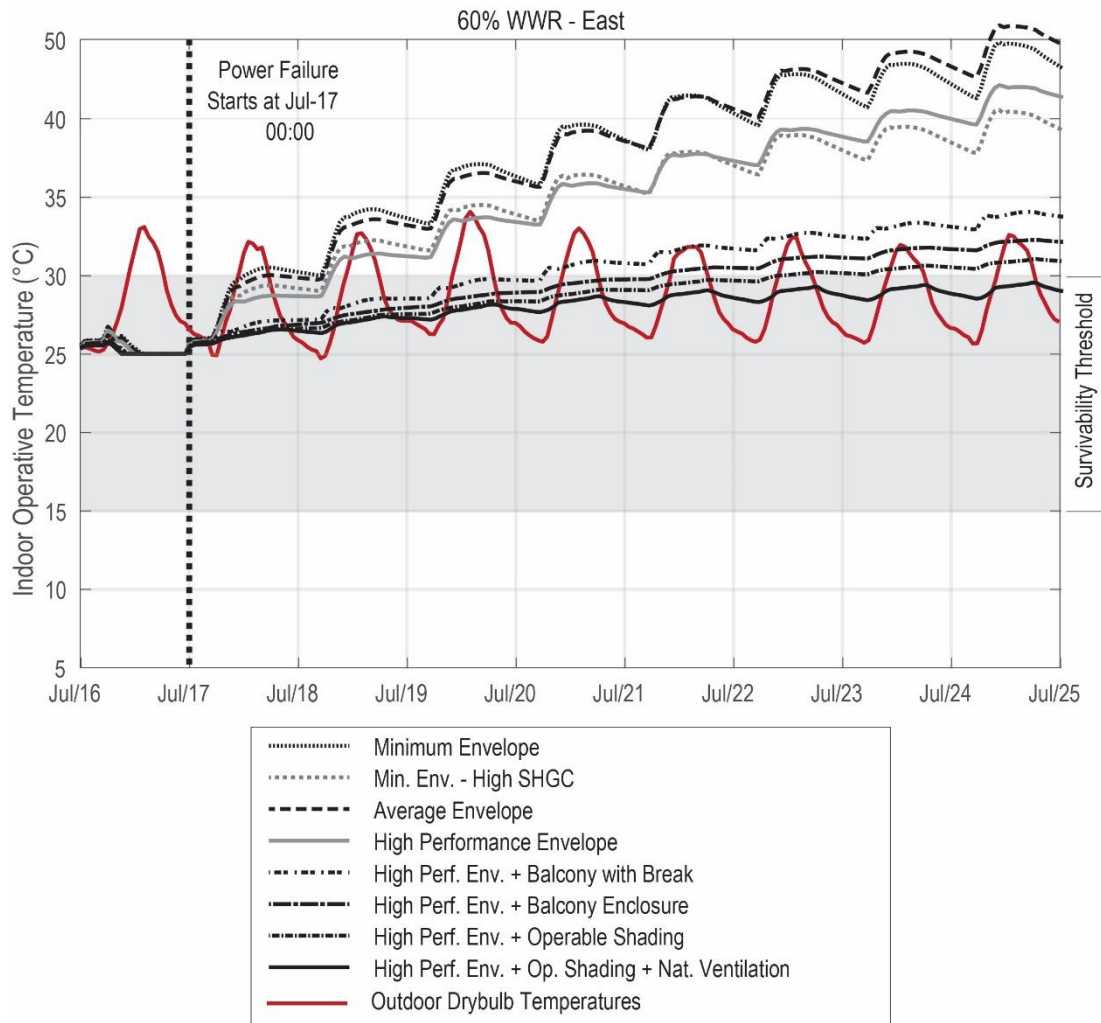


Figure C.40 : Passive survivability performance for an east-facing unit with 60% WWR under summer conditions in Adana.

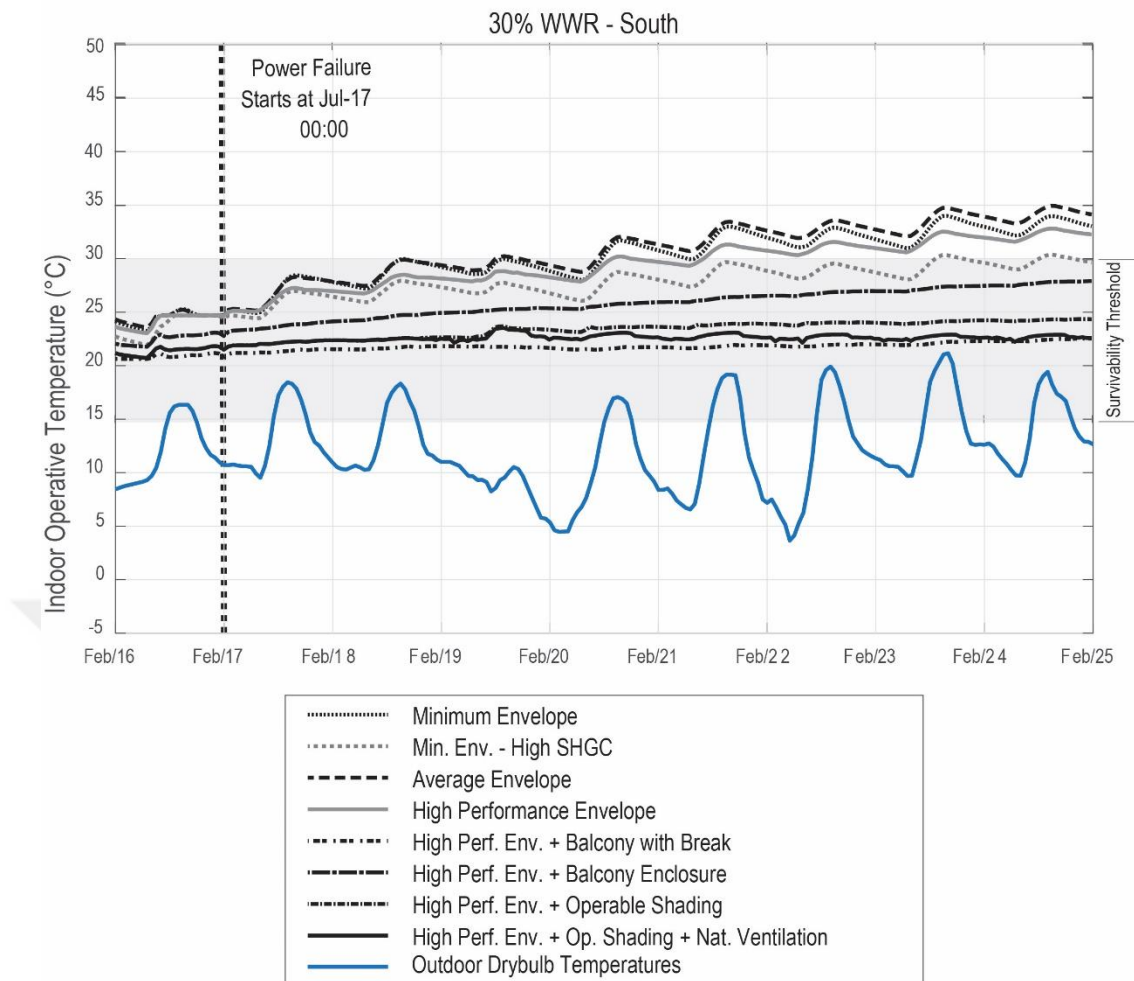


Figure C.41 : Passive survivability performance for a south-facing unit with 30% WWR under winter conditions in Adana.

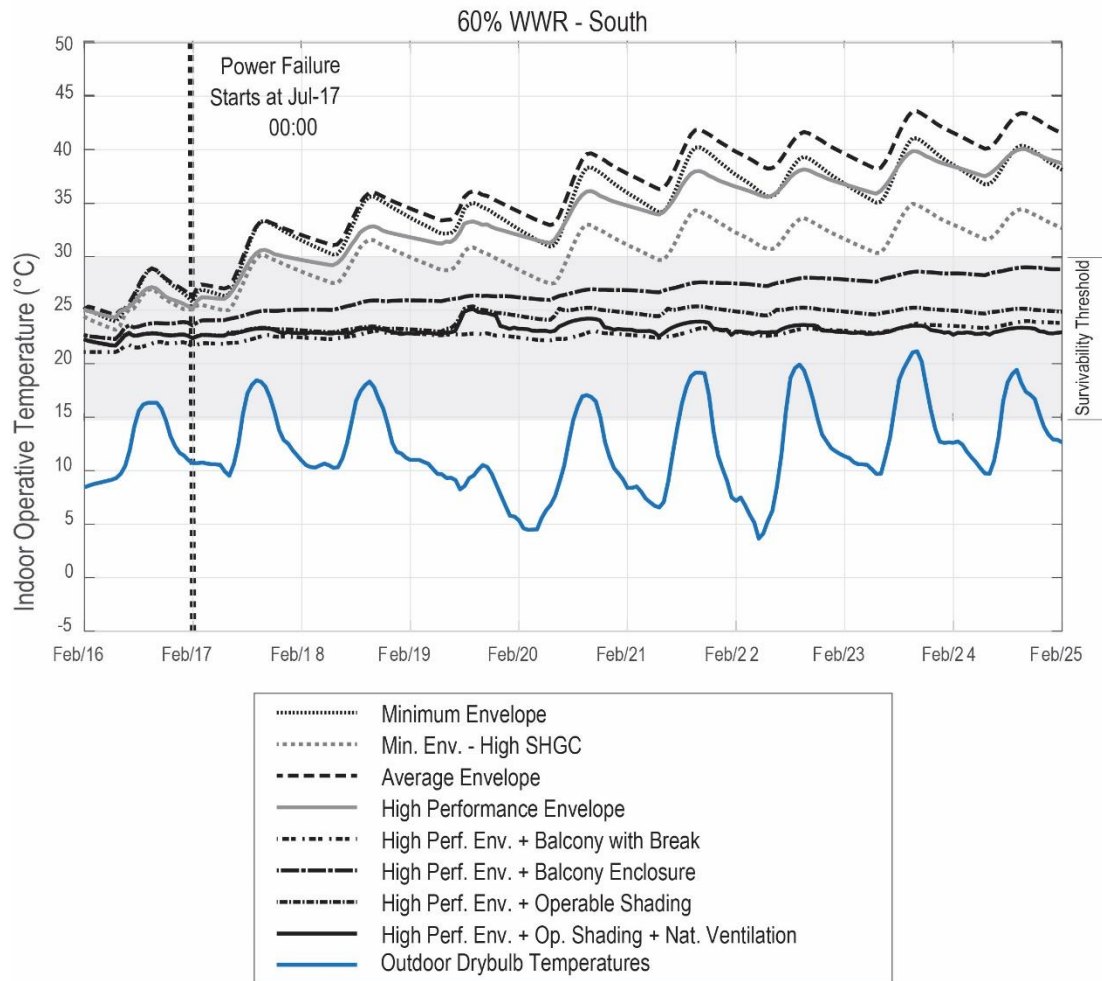


Figure C.42 : Passive survivability performance for a south-facing unit with 60% WWR under winter conditions in Adana.

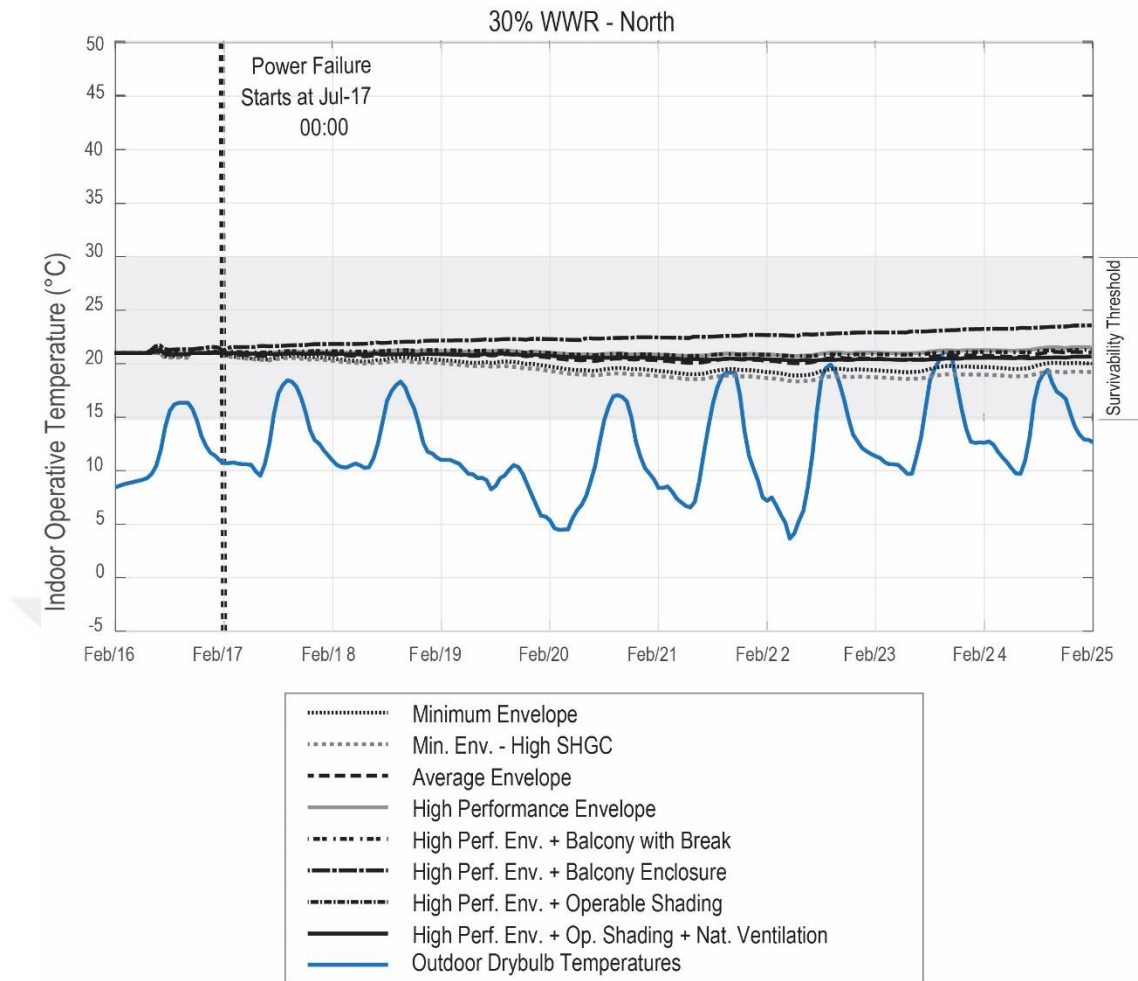


Figure C.43 : Passive survivability performance for a north-facing unit with 30% WWR under winter conditions in Adana.

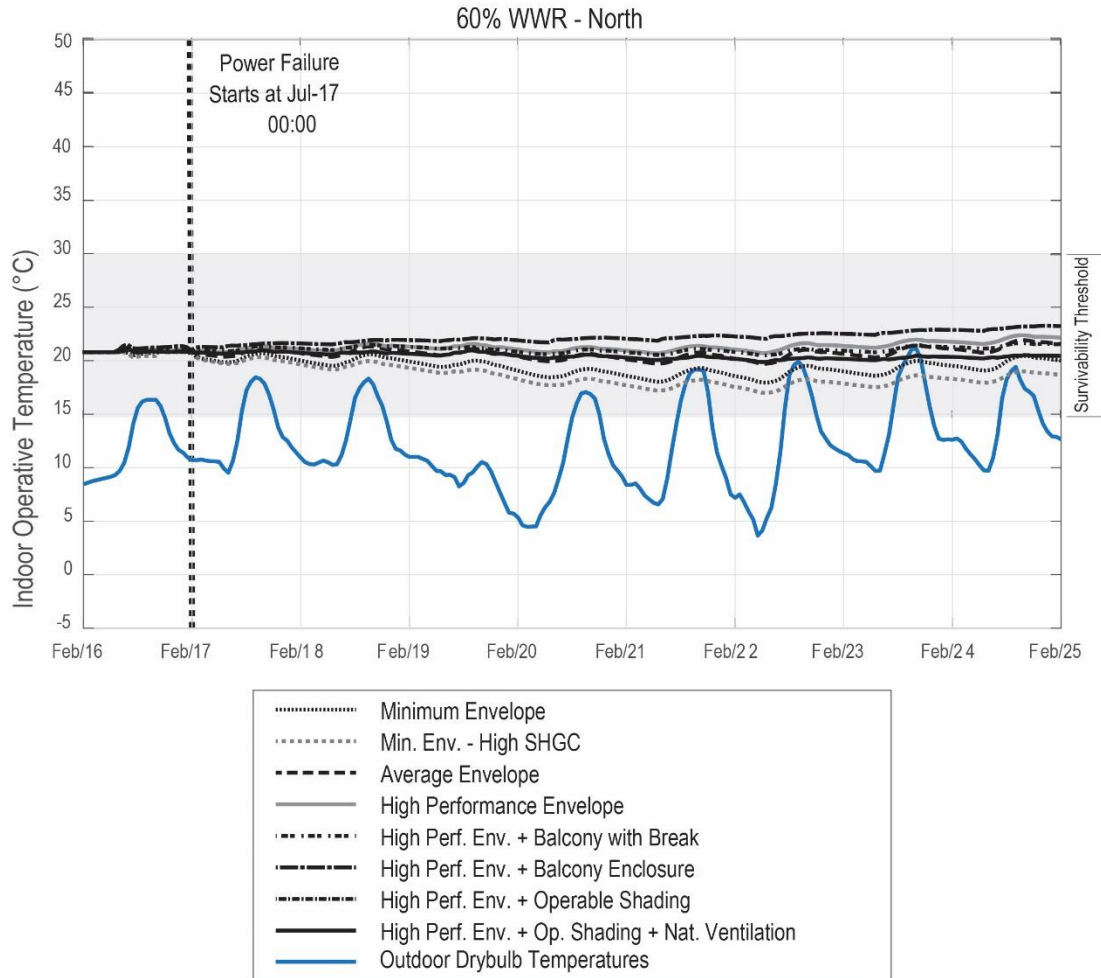


Figure C.44 : Passive survivability performance for a north-facing unit with 60% WWR under winter conditions in Adana.

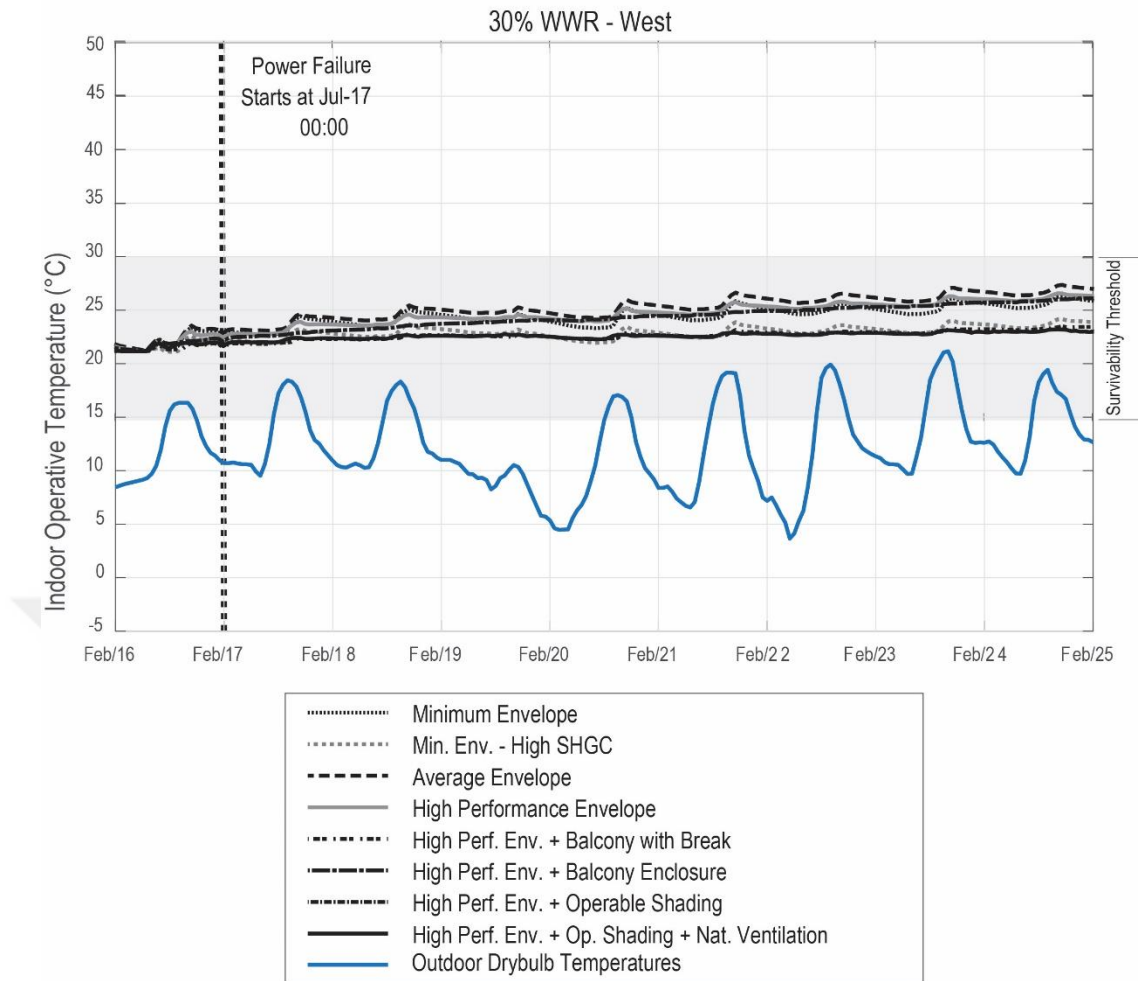


Figure C.45 : Passive survivability performance for a west-facing unit with 30% WWR under winter conditions in Adana.

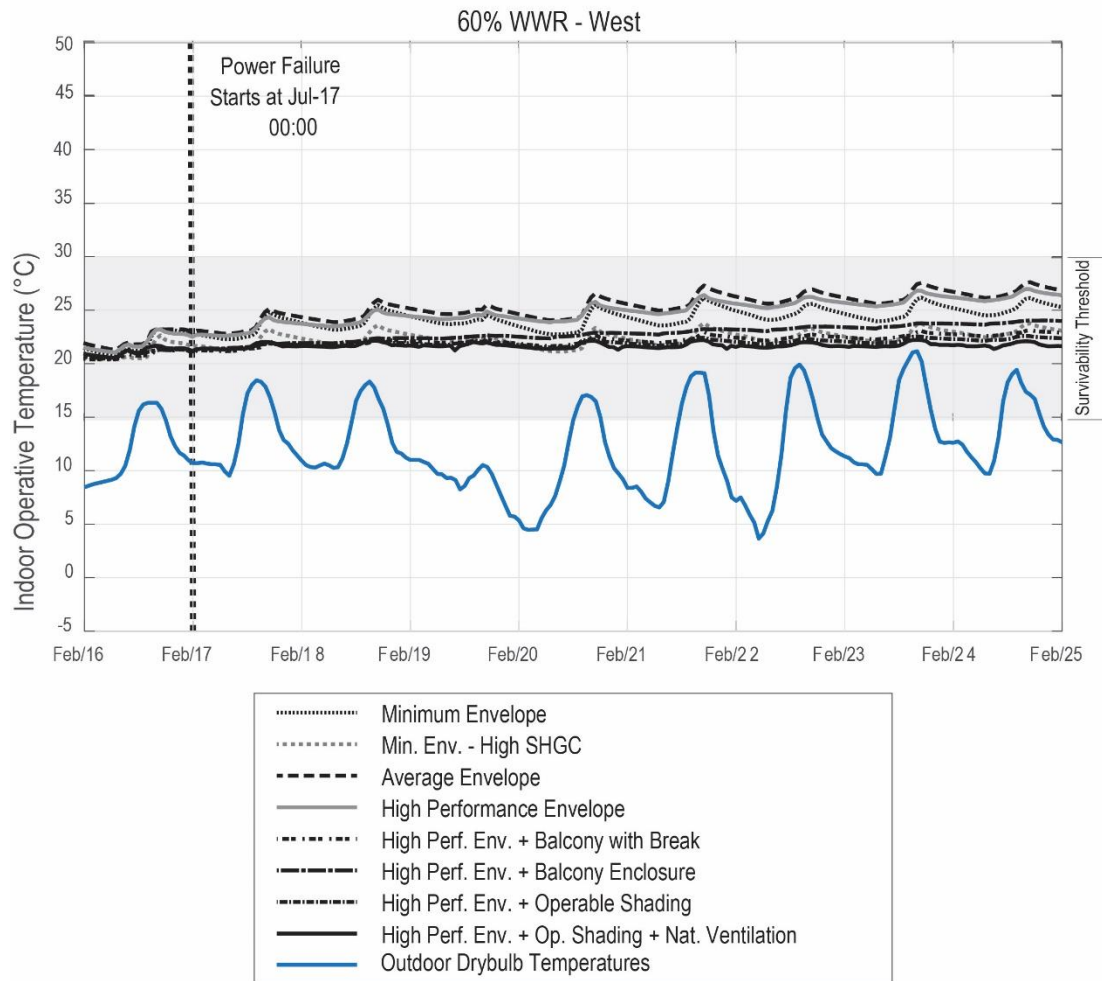


Figure C.46 : Passive survivability performance for a west-facing unit with 60% WWR under winter conditions in Adana.

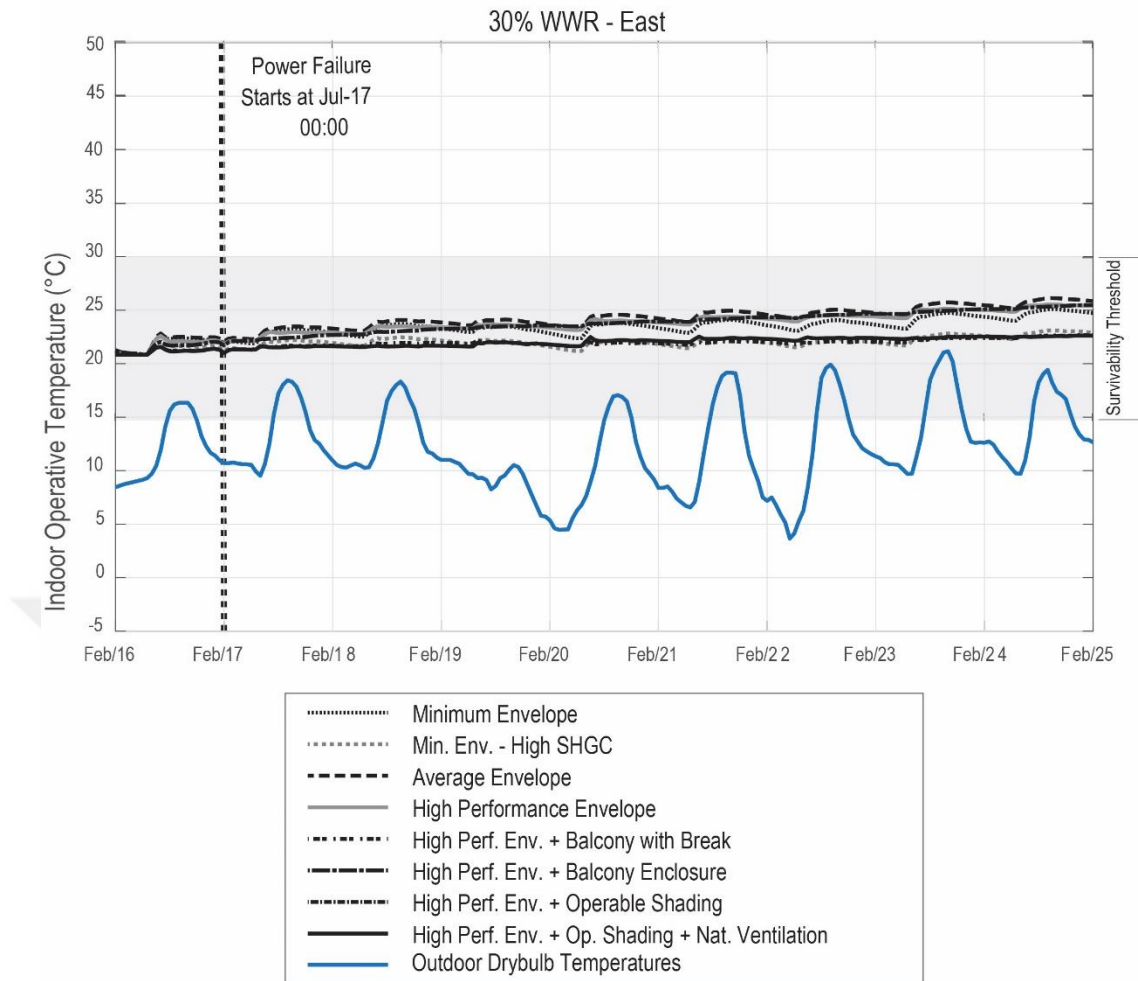


Figure C.47 : Passive survivability performance for an east-facing unit with 30% WWR under winter conditions in Adana.

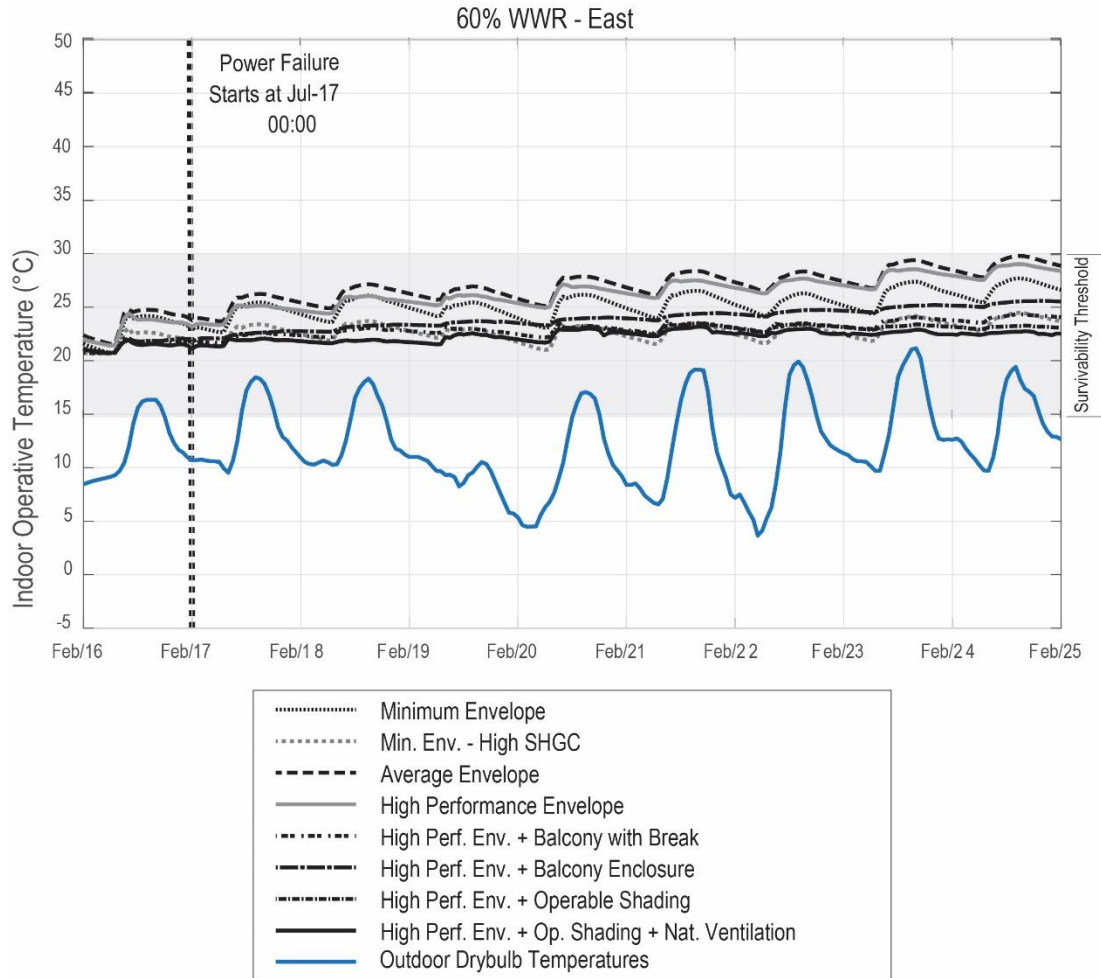


Figure C.48 : Passive survivability performance for an east-facing unit with 60% WWR under winter conditions in Adana.

APPENDIX D : Matlab Code for PS graphs

The coding for PS graphs is created in MATLAB as presented below.

```
cd('C:\Users\Aylin\Dropbox\aylin\plot-matlab\PS_GRAPH')
startDate = datenum('02/16/2002 00:00');
endDate = datenum('02/25/2002 00:00');
xData = linspace(startDate,endDate,10);

formatSpec = '%{dd/MM/yyyy HH:mm}D%f%f%f%f%f%f%f%f%f%f';
results=readtable('south.dat','Format',formatSpec);

xx=datenum(results.Var1(1104:1343));
yy1=results.Var3(1104:1343);
yy2=results.Var7(1104:1343);
yy3=results.Var5(1104:1343);
yy4=results.Var4(1104:1343);
yy5=results.Var12(1104:1343);
yy6=results.Var13(1104:1343);
yy7=results.Var9(1104:1343);
yy8=results.Var10(1104:1343);

h=figure;
hold off

plot(xx,yy6,'DisplayName','Minimum Envelope','Linewidth',3,...
     'Color',[1 0 0]);
hold on
plot(xx,yy3,'DisplayName','Min. Env. + High SHGC','Linewidth',3,...
     'Color',[1 0.5 0.25]);
plot(xx,yy5,'DisplayName','Average Envelope','Linewidth',3,'Color',[0.8 0.7 0.6]);
plot(xx,yy1,'DisplayName','High Performance Envelope','Linewidth',3,'Color',[0.6 0.5
0.4]);
plot(xx,yy2,'DisplayName','High Perf. Env. + Balcony with Break',...
     'Linewidth',3,...
     'Color',[0.75 0.75 0]);
plot(xx,yy7,'DisplayName','High Perf. Env. + Balcony Enclosure','Linewidth',3,...
     'Color',[0.75 0 0.75]);
plot(xx,yy8,'DisplayName','High Perf. Env. + Operable Shading','Linewidth',3,...
     'Color',[0 0.7 0.7]);
plot(xx,yy4,'DisplayName','High Perf. Env. + Op. Shading + Nat.
Ventilation','Linewidth',3,...
     'Color',[0 0 1])

ax = gca;
ax.XTick = xData;
datetick('x','mmm/dd','keepticks')

% Create title
title({'30% WWR - Winter'},'FontSize',14);
% Create ylabel
ylabel({'Indoor Operative Temperature (°C)'},'FontSize',14,'Linewidth',2,...
```

```

    'Fontweight','bold');

box('on');
grid('on');

% Create legend
legend1 = legend('show');
%columnlegend(2,legend1.String,'Location','southoutside','padding', 0.10);

set(legend1,...
    'Position',[0.611782178370656 0.718541759763825 0.285687458936117
0.192931262435616],...
    'FontSize',12);set(legend1,'Location','southoutside')

% Create line
annotation('line',[0.215761073573573 0.215761073573573],...
    [0.923777884830945 0.109113933710777],'color',[0 0.498039215803146 0],...
    'Linewidth',3,...
    'LineStyle',':');

% Create textbox
annotation('textbox',...
    [0.133557424688929 0.843091334894627 0.0805050753110705 0.0757173615606939],...
    'color',[0 0.498039215803146 0],...
    'String',{'Power Failure Starts'},...
    'Linewidth',3,...
    'HorizontalAlignment','center',...
    'Fontweight','bold',...
    'FontSize',11,...
    'FitBoxToText','off',...
    'EdgeColor','none');

ylim([0 60]);

cd('C:\Users\Aylin\Dropbox\aylin\plot-matlab\PS_GRAPH')
startDate = datenum('07/16/2002 00:00');
endDate = datenum('07/25/2002 00:00');
xData = linspace(startDate,endDate,10);

formatSpec = '%{dd/MM/yyyy HH:mm}D%f%f%f%f%f%f%f%f%f%f';
results=readtable('south.dat','Format',formatSpec);

xx=datenum(results.Var1(4704:4943));
yy1=results.Var3(4704:4943);
yy2=results.Var7(4704:4943);
yy3=results.Var5(4704:4943);
yy4=results.Var4(4704:4943);
yy5=results.Var12(4704:4943);
yy6=results.Var13(4704:4943);
yy7=results.Var9(4704:4943);
yy8=results.Var10(4704:4943);

figure
hold off
plot(xx,yy6,'DisplayName','Minimum Envelope','Linewidth',3,...
    'color',[1 0 0]);
hold on
plot(xx,yy3,'DisplayName','Min. Env. + High SHGC','Linewidth',3,...

```

```

        'Color',[1 0.5 0.25]);
plot(xx,yy5,'DisplayName','Average Envelope','Linewidth',3,'Color',[0.8 0.7 0.6]);
plot(xx,yy1,'DisplayName','High Performance Envelope','Linewidth',3,'Color',[0.6 0.5
0.4]);
plot(xx,yy2,'DisplayName','High Perf. Env. + Balcony with Break',...
    'Linewidth',3,...
    'Color',[0.75 0.75 0]);
plot(xx,yy7,'DisplayName','High Perf. Env. + Balcony Enclosure','Linewidth',3,...
    'Color',[0.75 0 0.75]);
plot(xx,yy8,'DisplayName','High Perf. Env. + Operable Shading','Linewidth',3,...
    'Color',[0 0.7 0.7]);
plot(xx,yy4,'DisplayName','High Perf. Env. + Op. Shading + Nat.
Ventilation','Linewidth',3,...
    'Color',[0 0 1])

ax = gca;
ax.XTick = xData;
datetick('x','mmm/dd','keepticks')

% Create title
title({'30% WWR - Summer'},'FontSize',14);

% Create ylabel
ylabel({'Indoor Operative Temperature (°C)'},'FontSize',14,'Linewidth',2,...
    'FontWeight','bold');

box('on');
grid('on');

% Create legend
legend1 = legend('show');
set(legend1,...
    'Position',[0.611782178370656 0.718541759763825 0.285687458936117
0.192931262435616],...
    'FontSize',12);set(legend1,'Location','southoutside')

% Create line
annotation('line',[0.215761073573573 0.215761073573573],...
    [0.923777884830945 0.109113933710777],'color',[0 0.498039215803146 0],...
    'Linewidth',3,...
    'LineStyle',':');

% Create textbox
annotation('textbox',...
    [0.133557424688929 0.843091334894627 0.0805050753110705 0.07571736156069395],...
    'Color',[0 0.498039215803146 0],...
    'String',{'Power Failure Starts'},...
    'Linewidth',3,...
    'HorizontalAlignment','center',...
    'FontWeight','bold',...
    'FontSize',11,...
    'FitBoxToText','off',...
    'EdgeColor','none');

ylim([15 60]);

```



CURRICULUM VITAE



Name Surname : Aylin Ozkan
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EDUCATION

- **B.Sc.** : 2008, Gazi University, Architecture.
- **M.E.B.D.** : 2011, University of Pennsylvania, Master in Environmental Building Design, Architecture.

PROFESSIONAL EXPERIENCE AND REWARDS:

- **Research Associate:** July 2016 to continues in 2018, University of Toronto, Daniels Faculty of Architecture
- **Research Assistant:** October 2015 to June 2016, University of Toronto, Daniels Faculty of Architecture
- **Guest Instructor:** Winter 2016, Ryerson University, Department of Architectural Science. (BL8104 Buildings Design Seminar / Studio)
- **Sustainable Building Advisor:** January 2015 to September 2015, Perkins+Will, Toronto, ON.
- **Research Assistant:** January 2013 to September 2014, Erciyes University, Faculty of Architecture, Kayseri, Turkey.
- **Architect:** Summer 2010, DCM Architecture & Engineering LLC, Camden, NJ, USA.
- **Intern StudentArchitect:** 06/2006 to 06/2008, Yontem Architecture Company, Ankara, Turkey.
- **Prize:** 1st prize at Afyonkarahisar School Complex Architectural Project Competition, June 2013.

- **Grant:** Graduate Fellowship, the Republic of Turkey Ministry of Education, 08/2010 – 07/2011.

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Ozkan, Aylin,** 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](https://doi.org/10.1080/09613218.2018.1451959)
- **Ozkan, A.,** Kesik, T., & O'Brien, W. (2016). The influence of passive measures on building energy demands for space heating and cooling in multi-unit residential buildings. Proceedings of the eSim 2016 Building Performance Simulation Conference, May 3–6, McMaster University, Hamilton, Ontario, Canada.
- **Ozkan, A.,** Yilmaz, Z., Kesik, T., & O'Brien, W. (2017). The time-based metrics of thermal autonomy and passive survivability and their correlation to energy use intensity. ICBEST, Istanbul, 15–18 May, 2017.
- **Ozkan, A.,** Kesik, T., & O'Brien, W. (2017). Visualization of passive performance parameters through time-based metrics and discussion of a survey for validation of the approach. Proceedings of the 15th IBPSA Conference San Francisco, CA, USA, Aug. 7–9.

OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS:

- Buyukmihci G., Salgin B., **Ozkan A.** (2015) Yeşil Çatı Çözümlerinin Tarihi Dokularda Geleneksel Çatı Örtüsü Olarak Uygulanabilirliği Üzerine Bir İnceleme, Erciyes Üniversitesi Fen Bilimleri Enstitüsü Dergisi, cilt.31, ss.163-171, 2015.
- Buyukmihci G. & **Ozkan A.** (2013) Integrity of Conservation and Sustainability Techniques in a Special Historic Site, with Gonca Buyukmihci, Built Heritage 2013 - Monitoring Conservation and Management, Italy, November 2013.
- Trubiano, F., Sadeghipour M. & **Ozkan A.** (2013) Integrating Building Simulation and Evolutionary Optimization in the Conceptual Design Phase of a High-Performance Office Building, IBPSA-2013 Conference, France, August 2013.