Thermal Autonomy as Metric and Design Process

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Proceedings of Pushing The Boundaries: Net Positive Buildings, SB13, Vancouver, 2013

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ABSTRACT: Metrics for quantifying thermal comfort and energy consumption focus on the role of mechanical systems, not architecture. This paper proposes a new metric, "Thermal Autonomy," that links occupant comfort to climate, building fabric, and building operation. Thermal Autonomy measures how much of the available ambient energy resources a building can harness rather than how much fuel heating and cooling systems will consume. The change in mental framework can inform a change in process. This paper illustrates how Thermal Autonomy analysis gives rich visual feedback as to the diurnal and seasonal patterns of thermal comfort that an architectural proposition is expected to deliver. Thermal Autonomy has far-reaching utility as a comparative metric for envelope design, identifying mechanical strategies, and mixed-mode operation decisions. Foremost, it is a generative metric to quantify ways that the building filters the ambient environment. The use of Thermal Autonomy is illustrated through parametric building thermal simulation and analysis.

INTRODUCTION

There is a need for the fundamental re-alignment of how we measure and think about thermal comfort in buildings. Most existing metrics were developed to inform the design of mechanical systems. Occasionally, metrics are proposed that define when people are likely to be comfortable without heating or cooling systems, but these metrics are framed to avoid energy use rather than embrace the opportunities of climate. No existing comfort metric relates the building fabric and the occupant to the climate. As a result, existing metrics tell us little about how a building design might perform independent from mechanical systems.

This paper introduces the concept of Thermal Autonomy as both a metric and a design process. Thermal Autonomy is the ability for a space to provide acceptable thermal comfort through passive means only. More broadly, the process of designing for Thermal Autonomy represents a fundamental shift in understanding building performance - one that prioritizes the building fabric as a selective filter for the ambient environment to provide occupant comfort.

Building thermal performance is a complex phenomenon involving thousands of physical interactions at any given moment. To compound the complexity, occupant thermal comfort is spacio-temporal - neither a snapshot, a summary, nor an average can tell the whole story. Diurnal, weekly, and seasonal patterns must be understood. To accomplish this for the 8,760 hours in a year, sophisticated graphical representations of the data are required.

The concepts and techniques presented here were born of practical necessity as well as theoretical discourse. As a firm located in the San Francisco Bay Area, many of our projects are in California coastal climates that should not require building heating or cooling much of the year. In spite of this, most buildings are extensively conditioned even in these climates. Thermal Autonomy is a concept developed to show our clients - architects, engineers, and building owners - the patterns, degree, and quantity of thermal comfort for a given design. Even in our work in more extreme climates, such as New York or India, we have found that Thermal Autonomy, in concept and practice, is applicable and potent.

We often liken Thermal Autonomy to sailing. While modern sailboats are equipped with motors for days without wind, design of the boat is optimized for sail-driven locomotion. So too should buildings be able to "sail" using the "free" energy of wind, air, sun, and internal heat sources to temper the indoor environment. The resultant autonomy is not just a building that is self-reliant but one that is calibrated to the climatic context, connecting occupants to the changing weather.

BACKGROUND

As the building industry has slowly come to understand the connections among thermal comfort, heating and cooling systems, energy consumption, and greenhouse gas emissions, there has been increased urgency for sophisticated comfort definitions. There are currently two branches of thermal comfort indices: those for conditioned and those for naturally ventilated buildings.

Modern comfort metrics for conditioned buildings derive from Ole Fanger's 1967 comfort model. Based on physiological research of subjects in mechanically conditioned environments, this model has been used to better understand the range of environmental conditions that building mechanical systems must provide to minimize the number of occupant complaints. The Fanger comfort model predicts how dissatisfied an occupant is likely to say they are on a 7-point scale between "hot" (+3) and "cold" (-3). This scale has been statistically correlated to the percentage of people likely to be dissatisfied in a space (Rohles et al., 1975). Standards such as ASHRAE-55 and EN 15251 recommend that environmental systems be engineered to ensure less than a given percentage of occupants are likely to be dissatisfied. Thus we arrived at a situation wherein a statistical probability of comfort can be correlated to a range of temperatures and humidities 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. This represents a profound shift in focus from occupant comfort to HVAC system performance.

Research has shown that occupants in naturally ventilated buildings experience an expanded sense of thermal comfort when they have access to operable windows. This is due to adaptation to, as well as perceived control of, their thermal environment (deDear & Brager, 1998). With the publication of the adaptive comfort model and the formal incorporation of this thinking into standards and codes, the industry is beginning to re-accept the possibility of unconditioned buildings for the first time since the widespread introduction of air-conditioning in the 20th century.

Like the Fanger comfort model, the adaptive comfort model has been statistically correlated to a percentage of occupants likely to be dissatisfied. This allows for the quantification of hours beyond an acceptable limit as a single number. The contingencies and subtleties of both comfort models are thereby lost as single-number metrics become the principle method of describing performance requirements. While this can be useful for benchmarking, this paper shows how single-number metrics have limited utility as design informants.

METHODS

Thermal Autonomy as a metric and design process is explained here through the lens of a schematic design for a classroom in Oakland, California. For this study, Thermal Autonomy is 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.*

In this example it is more narrowly defined as the percent of occupied hours during a Typical Meteorological Year when a Mixed Air Thermal Zone meets or exceeds 80% acceptability criteria for adaptive thermal comfort.[1] The thermal zone includes no heating or cooling systems, and it is assumed that fresh air demands are met with trickle vents (modeled as a constant supply of ventilation air during occupied hours).

Thermal Autonomy, as a concept, posits all buildings as initially unconditioned and naturally ventilated. Even spaces without any practical ability to open windows can be understood in terms of Thermal Autonomy, or lack thereof. Stripping a building of its mechanical systems, if only as a thought exercise, can shine a brighter light on the deficiencies or limits of a building envelope or operational strategy.

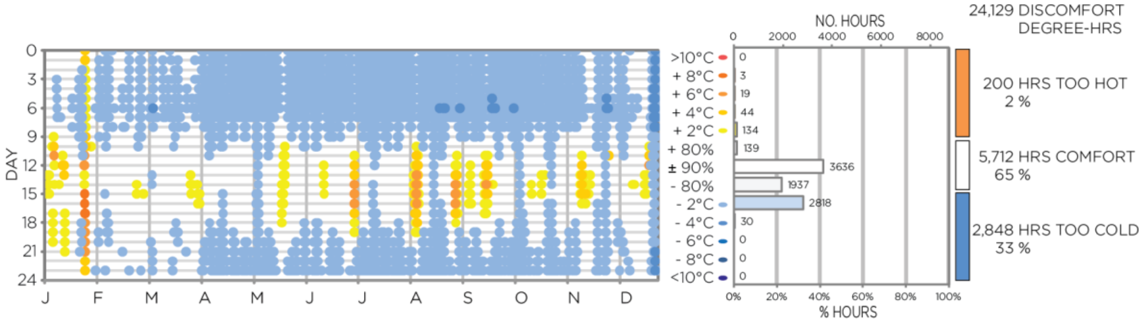

Figure 1. Sample visualizations of Thermal Autonomy. In tandem, the heat map (left) and histogram (right) present the complexity of a space's thermal autonomy.

Graphs are used to visualize and interpret the simulation results (Fig. 1). The heat map on the left charts the days of the year on the X-axis against hours of the day on the Y-axis. Each circle is an hour of discomfort and the hue indicates degree of discomfort. The chart facilitates the reading of diurnal, weekly, and seasonal patterns. Coupled with an understanding of the climate and building being modeled, the visualization helps us to identify appropriate architectural and operational responses, such as increased shading or shifting occupancy schedules.

The histogram on the right groups all hours of the year according to degree from the 80% acceptability range. While the heat map reveals the patterns of comfort, the histogram reveals the extent. It gives a meaningful summary of conditions outside the comfort zone and helps quantify the effects of parametric changes to the building.

On the extreme right, three types of single-number metrics are reported relative to comfort critera: (A) weighted degree-hours, (B) number of occupied hours, and (C) percentage of occupied hours. These are the metrics defined by EN 15251, the European standard for thermal comfort performance. The following study reports these aggregated numbers along with data visualizations, and the utility of these metrics are explored in the Discussion section.

A classroom design in Oakland, California

The Oakland Unified School District started to develop a masterplan for a new high school and asked how they could make it more sustainable. We used the concept of Thermal Autonomy to show how a typical classroom in the masterplan would perform without heating or cooling systems. The masterplan was well-designed to meet a functional program, typical wood-frame construction methods, and address a challenging urban and social context. Different operational and building envelope scenarios were tested on the masterplan and select results are presented here.

In order to design a thermally autonomous building, it is important to consider the climatic context. Work on the classroom began with a detailed analysis of the climate based on first-hand observation and close readings of the Typical Meteorological Year (TMY) data. Oakland's climate is characterized by mild temperatures modulated by the large masses of the Pacific Ocean and the Central Valley of California (Fig. 2).

There are two distinct seasons: a rainy winter extending from December to April and a dry summer from April to November. Most of Oakland's rainfall occurs during the winter months with an annual accumulation of about 50 cm. During winter rain events the wind is variable and gusty. Even with all the rain, about 30-50% of the winter days are clear or partly cloudy. Regardless, the temperature usually stays between 10 and 15°C during the day and 5 to 10°C during the night.

Less than 2 cm of rain typically falls between April and November. In these dry summer months morning fog is common and it burns off by late morning. These mornings are brisk with temperatures between 10 and 15°C. By afternoon temperatures rise into the 20's with a consistent breeze from the west-northwest. Nights are often clear and cool with temperatures dropping back into the teens.

As early as May, but more often in late August, September, and early October, Oakland experiences a series of 3-4 day events called "heat storms." These days are marked by high temperatures around 30°C, clear skies, and little wind. During these events temperatures drop about 10°C at night.

In spite of Oakland's cool climate, the building bioclimatic chart (Fig. 3) shows that buildings can help keep people comfortable without significant heating or cooling. Highlighted regions of the psychrometric chart show that a well-insulated building with properly-oriented glass and mass for passive solar heating can keep people warm most of the year, though supplementary heating is required at times. In addition, natural ventilation can keep people cool enough except during heat storm events. During these periods shaded thermal mass that is purged of heat at night can provide comfort.

Four classroom scenarios were analyzed for a variety of orientations and building proportions: (1) a baseline building, (2) a baseline building with natural ventilation, (3) a climate-

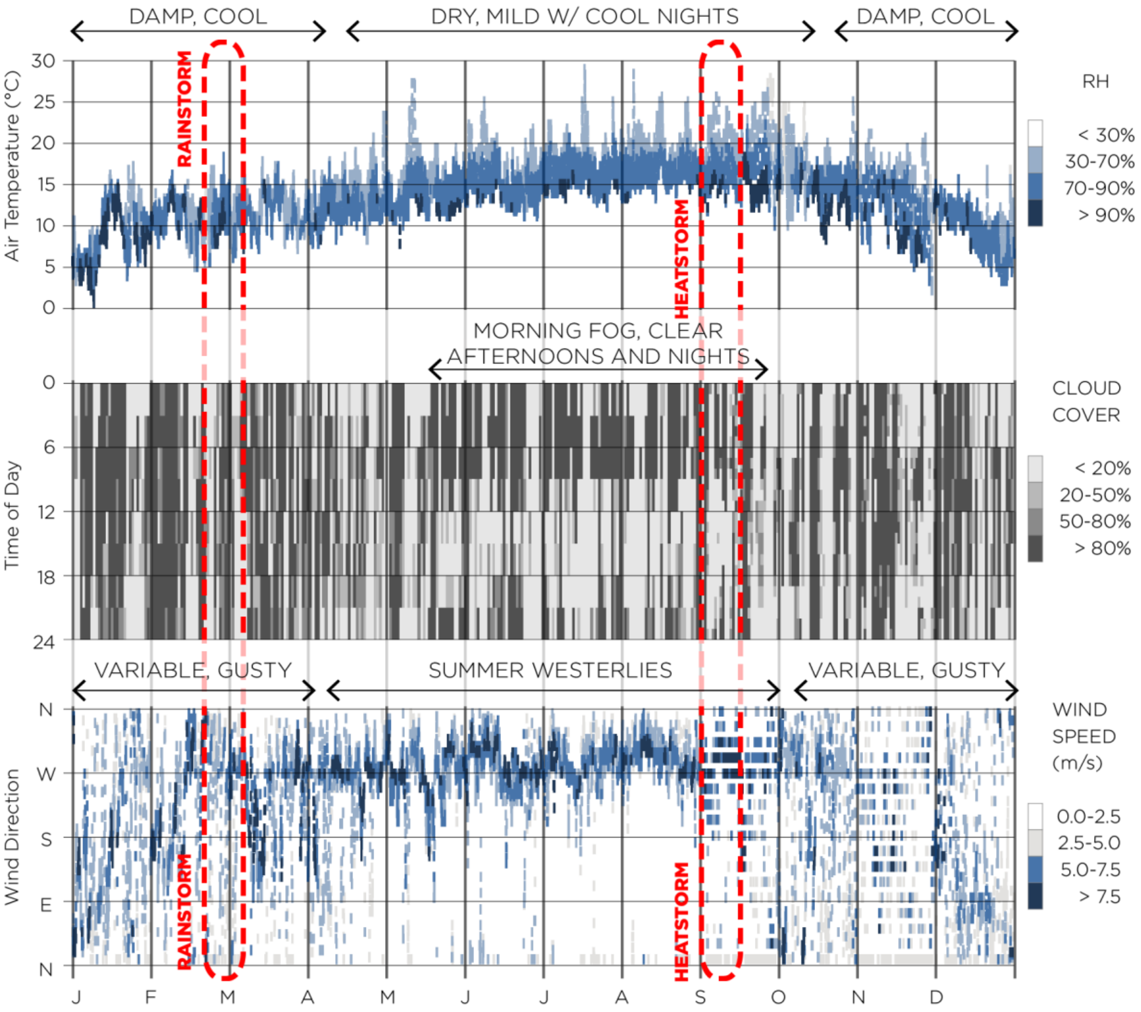

Figure 2. Analysis of Oakland Typical Meteorological Year (TMY). The analysis illuminates weather patterns and events that are likely to affect building performance strategies. Emphasis is placed on diurnal and seasonal patterns of air temperature, humidity, cloud cover, and wind. Analysis focuses on two events that define the Oakland climate - cold winter rain storms and early fall heat storms.

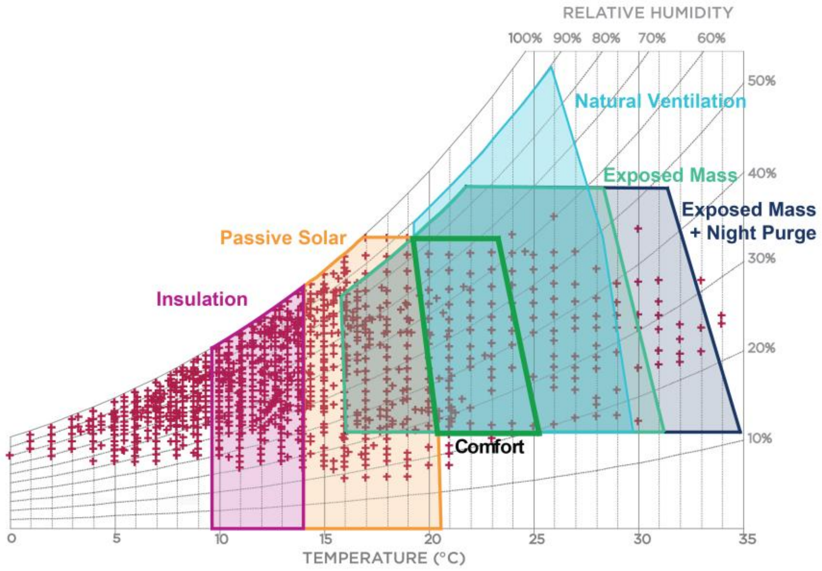

Figure 3. Building Bioclimatic Chart. Hourly TMY data with passive strategy overlays

responsive building, and (4) a climate-responsive building with school year occupancy. For the example presented here, the process is illustrated by a 7.3 m deep by 12.2 m long by 3.66 m high classroom with a large 2.75 m by 12 m window wall facing due south. The initial thermal simulation assumed a code-compliant building envelope with no overhangs and little thermal mass.[2]

Thermal simulations were calculated using EnergyPlus, a subhourly heat and mass balance simulation engine. Results were compiled and post-processed using custom scripts to calculate ΔT of the indoor operative temperature compared to comfort temperature as defined by the ASHRAE -55 Adaptive Comfort Standard. Thermal Autonomy Discomfort Degree Hours were defined as degrees from T_{comf} (17.8°C + 0.31 x T_m, where T_m is the monthly average of the daily average outdoor dry bulb temperatures).

In the case of this public school classroom, it was clear that the occupants would have the ability to adapt their clothing to the climate as well as operate windows. Based on this the 80% acceptability limits were used to define the comfort zone (±3.5°C from T_{comf}). When occupant expectations and adaptability are not as clear cut, one of the strengths of this process is that it requires dialogue among the designers, owners and/or occupants to set appropriate occupant thermal expectations from an early design stage.

Figure 4 shows the results of the first simulation. The indoor operative temperature is consistently over 35°C - more than 10°C above the upper limits of the comfort zone. The color-coded heat map in Figure 5 is saturated with red, indicating gross overheating for most of the year. The histogram reveals that there are only 905 hours of comfort conditions, or just 10% of the year.

Why so much overheating in such a benign climate? The classroom that is modeled does not have a heating or cooling system and ventilation air is only supplied to code minimum levels for fresh air.[3] By adding natural ventilation in the second run, hot air is effectively exhausted for much of the year. 81% of the annual hours are now comfortable, but 17% of the year is still overheating. The yellow and orange colors in the heat map in Figure 6 reveal the patterns. At a glance, it is obvious that discrete afternoons throughout the year are too hot with the worst overheating from September through November. By comparing the results with the climate data in Figure 2, one can see that afternoons of overheating correspond to outside temperatures above 21°C and clear skies.

Using this information, effective building strategies for achieving thermal comfort can be prioritized. In this case, a sensitivity analysis helped identify appropriate climate responses within the general parameters of the baseline building's dimensions and materials. The glass performance was improved, a 1.2 m horizontal overhang was added, insulation was added to the walls and roof, and the carpet was removed to expose the 10 cm-thick slab.

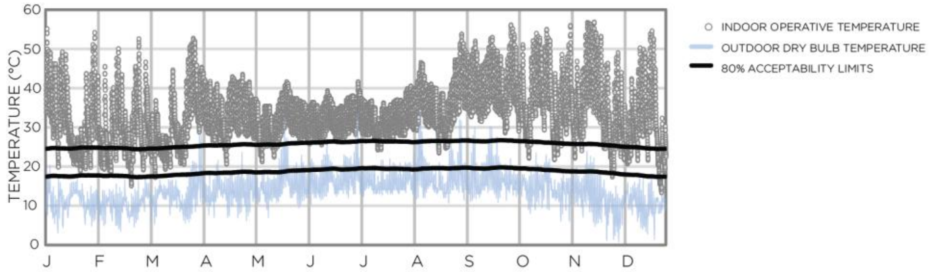

Figure 4. Baseline building, annual operative temperature and comfort zone

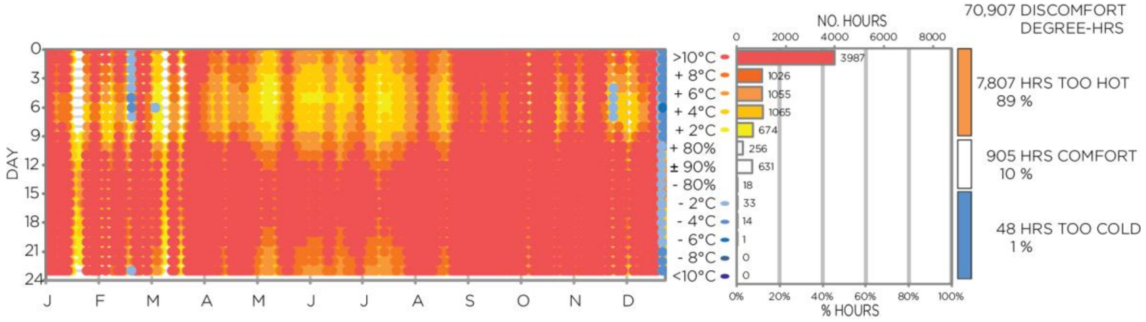

Figure 5. Scenario 1: Baseline Building

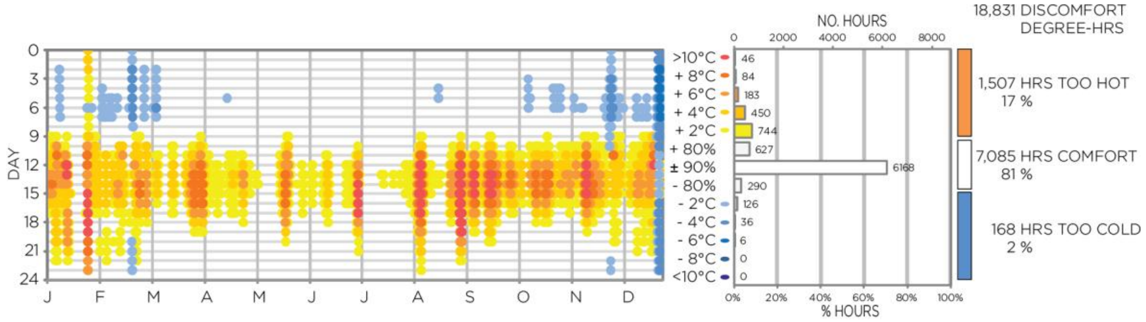

Figure 6. Scenario 2: Baseline building with natural ventilation

Different operating protocols for natural ventilation were explored in concert with the material changes. Night time ventilation coupled with increased thermal mass drives down the periods of overheating. This is apparent in Figure 7 where the bulk of uncomfortable hours lies in the evenings when windows are opened to purge the mass of excess heat. With this ventilation regime, periods of overheating occur on only 14 days in the afternoon. By accounting for a 2.2°C cooling effect due to air motion[4], the yellow dots would represent times of thermal comfort. This results in only 66 hours of overheating. Overlaying the occupancy schedule (8am-4pm during the spring and fall semesters) in Figure 8 reveals that only 57 hours of the year (during 6 days) overheat when the building is occupied.

DISCUSSION

The use of Thermal Autonomy as a design approach underlines the deficiencies of standard industry practice. Typical engineers would model the classroom with a complete heating, cooling, and ventilation system. This would mask the poor performance of the building envelope and lack of passive operation present in the initial run. The results would be presented as a bar chart of monthly energy use, abstracting the performance into a large amount of energy use dominated by cooling. If subsequent climate-responsive designs were modeled, the cooling loads would decline, but the specific patterns of afternoon overheating would not be apparent. Standard practice would dictate that a cooling plant be installed to meet whatever demand is present, not questioning the underlying assumptions of occupant comfort or building operation.

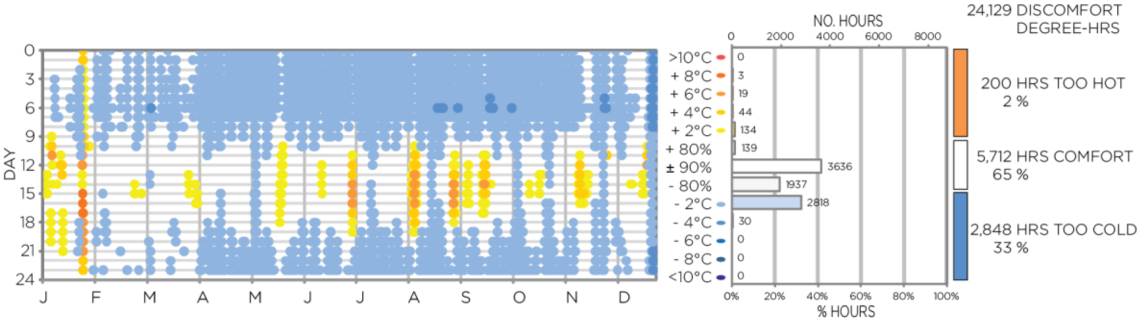

Figure 7. Scenario 3: Climate-responsive building with night ventilation

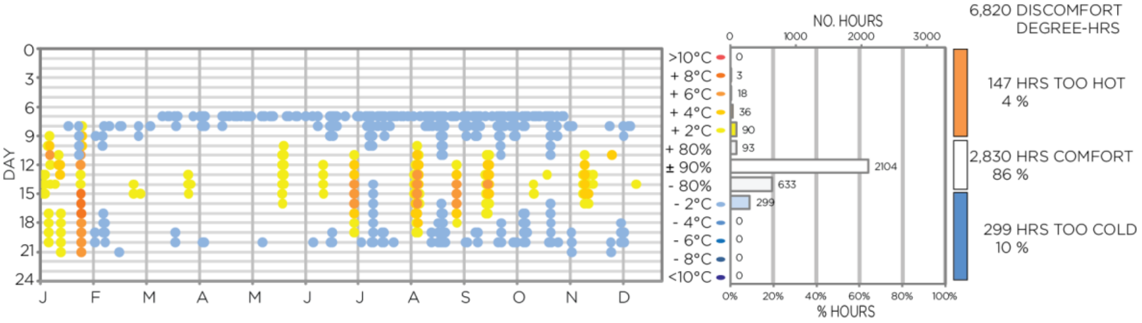

Figure 8. Scenario 4: Climate-responsive building with night ventilation, occupied hours only

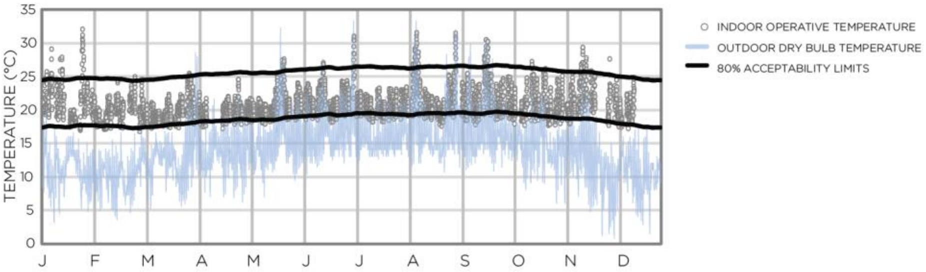

Figure 9. Climate-responsive building, annual operative temperature and comfort zone

The Thermal Autonomy analysis presents a fine-grained picture of building performance that is tangible and synchronous with common intuition, allowing informed decisions about the need for cooling. Given the results above, the school district has three options: install a cooling system for the six overheated days, adjust their occupancy schedule (i.e. hold classes outside during heat storm events), or adjust their thermal comfort criteria for these times of the year. Since the simulation showed that indoor operative temperatures peak at 32°C (Fig. 9), the client could make an informed and common sense decision about the classroom thermal environment. If similar thermal models had been run with full HVAC systems, the client would be forced to make a decision based on energy demand or capital cost. The analysis of Thermal Autonomy significantly changed the design and decision-making process.

Intrinsic to the Thermal Autonomy approach is the ability to see critical patterns in the simulation results. This is a two-part problem: first, the data must be graphically processed so that it can be clearly visualized, and secondly, the visualization must be correctly interpreted. Neither is a trivial task. By graphing hour, day, and degrees-from-comfort, the designer is able to see diurnal as well as seasonal effects. The scale of the representation also makes a difference: thumbnail images tell one story, while close, hour-by-hour reading can tell a more nuanced one. Further data manipulation through histograms tell a complimentary story, summarizing the finer grain information that our eyes and brains may not be able to discern. This summary information, when seen in tandem with the heat map, fills out a picture of the Thermal Autonomy.

It is important to note that the histogram in isolation does not supply enough information to be useful for design. By the same token a single number such as percent time comfortable or degree-hours from comfort may have utility as a standard or benchmark but is practically useless for informing a design approach. The results of the four scenarios are as follows:

Table 1. Summary of Thermal Autonomy results for 4 scenarios

Scenario	Thermal Autonomy (TA)	Degree Hours (TA_{ddh})
1	10%	70,905
2	81%	18,843
3	65%	24,183
4	86%	5,435

There is only a 5% increase in Thermal Autonomy between Scenarios 2 and 4, but a 3-fold decrease in Thermal Autonomy Discomfort Degree Hours. However, neither of these metrics tells us that Scenarios 3 and 4 would not require a cooling plant.

Understanding and/or creating client expectations is a critical part of the process. Some spaces might have strict requirements because of occupant clothing requirements, atypical metabolism levels, or increased thermal sensitivity due to age or health condition. The vast majority of building types can operate in a wider band of comfort expectations.

Furthermore, the potential for a program to adapt to a climate is an underexplored avenue. If the school day were moved two hours later, from 10am-6pm, the need for heating could be significantly reduced. Although this might be impractical for a school district, they might consider relaxing their comfort standards on hot days or holding classes outside. This underlines the role, not only of the designer, but also of the client and occupant in operating a sustainable building.

The classroom example underscores how sensitive Thermal Autonomy can be to operational schedules. As evidenced by Figures 7 and 8, comfort patterns differ depending on use. While the building might be designed for one type of operation, it likely will be adaptively reused at least once in its lifetime. That is not to say that operational patterns should be completely ignored - in the classroom example given, night ventilation would not have been a viable strategy had full annual operation been exclusively considered. Dynamic strategies that can change according to occupancy patterns enable a building to be more readily reused. We would therefore propose two distinct definitions of Thermal Autonomy: TA_{total} is the percent of time over a complete year, whereas $TA_{occupied}$ is the percent of time during occupied hours only.

Although this paper proposes Thermal Autonomy as an alternative metric to energy use, Thermal Autonomy as a concept is closely related to energy consumption. Every hour that is not thermally autonomous requires an energy input in order to achieve thermal comfort. The further from comfort, the more energy. By understanding degree and pattern, Thermal Autonomy provides clues for how to strategically deliver energy in an effective manner. For instance, the climate-responsive classroom is 2°C below comfort for an hour or two on most mornings. A short burst of heat to take the chill off is all that is required. More, and the classroom might overheat later in the day.

CONCLUSIONS

The primary purpose and utility of Thermal Autonomy is to provide an alternative approach to design by understanding performance in terms of occupant comfort, climate, building construction, and operation. Thermal Autonomy is not just a metric for quantifying performance, but a method for identifying the patterns of daily life that inform a design.

Rather than defining performance in terms of energy consumption or greenhouse gas emissions, this approach shifts the focus from energy systems to building construction and operation. The primary benefits include:

1. Envelope as environmental filter: By foregrounding the building envelope, insulation, shade, glass, ventilation, and thermal mass become the primary parameters for tuning a building to its climate.

2. Greater understanding of the impact of internal loads: Thermal Autonomy facilitates understanding of when the heat generated by people, lights, and equipment should be reduced, stored, or used for greater comfort.
3. Ease of interpretation: Even if "comfort" is notoriously difficult to define, it is an intuitive concept. Energy use, on the other hand, is an intrinsic abstraction that is once-removed from comfort and focuses on cost or emissions rather than occupants.
4. Rethinking assumptions: This process places an emphasis on occupant comfort and expectations, enabling designers and owners to rethink conventional defaults.
5. Gentle failure: In the event of an interruption in power or fuel, a thermally autonomous building will still provide comfort conditions.
6. Fewer active thermal systems: This process prioritizes envelope performance such that buildings require fewer (or no) active thermal systems.
7. Strategic use of active systems: Because these analysis techniques reveal the patterns of discomfort, mechanical systems can be strategically designed for the specific types of discomfort an occupant is likely to experience.
8. Extended free-running periods: Even in extreme climates there are usually swing seasons and/or parts of days when thermal comfort can be provided without mechanical systems. The Thermal Autonomy process can help extend free-running periods in Mixed Mode buildings.

Using Thermal Autonomy as a design metric and performance goal can change the conversation from limiting energy use to improving the quality of the environmental experience. Rather than an emphasis on mechanical systems, Thermal Autonomy privileges the occupant and the architecture. In a conventional design process the architect proposes a building fabric and the engineer designs a prosthetic mechanical system that remedially manufactures thermal comfort. Thermal Autonomy as a process posits the building fabric as the primary creator of comfort. This also shifts the conversation from one of problem-solution to generative design alternatives, engaging the design team as an integrated whole rather than an architect/creator and engineer/problem-solver.

FURTHER RESEARCH

This study has not attempted to benchmark Thermal Autonomy for different climates or building types. While we are wary of single-number building metrics, Thermal Autonomy might be a useful way of defining building performance for a given climate and program. It remains to be seen if Thermal Autonomy benchmarks could be used as minimum performance standards, but it would be interesting to see the patterns and degree of Thermal Autonomy for different buildings in different climates over a large sample size. Comparing these Thermal Autonomy numbers to Energy Use Intensity would, in turn, result in a greater understanding of both metrics.

The method and metrics outlined here were explained for a single thermal zone. It is possible to expand this logic to multi-zone buildings through the use of zone weighting. Although the patterns of Thermal Autonomy are still important to understand for each zone, one could distill a whole-building Thermal Autonomy metric by area-weighting and/or occupant-weighting each zone. The question of how to weight the zones is an important one that could potentially produce misleading results. Some comfort metrics, such as "Exceedance" (Borgeson & Brager, 2011), advocate for occupant-weighting. However, this method biases existing occupancy patterns over long-term whole-building performance. Further research using different building types, occupancy assumptions, and adaptive reuse scenarios is needed to validate a specific zone-weighting approach.

Another application for Thermal Autonomy is to better understand and classify Mixed Mode operation - buildings that operate as conditioned buildings for only part of the year. The heat map reveals what portions of the year are likely to require mechanical heating and cooling. Thermal Autonomy can help designers characterize the frequency and role that mechanical systems play.

It is with these questions in mind that we propose Thermal Autonomy as a metric and design process. The metric is a simple and intuitive measure that relates building performance, occupant thermal comfort, and climate. Though there are sophisticated and nuanced applications for the metric, we feel that its broad definition is a strength. As thermal comfort research continues to advance, Thermal Autonomy can reflect these changes along with simulation software and ultimately, the building design process.

ENDNOTES

[1] ASHRAE Standard 55 adaptive comfort model states that "the 80% acceptability limits are for typical applications and shall be used when other information is not available. It is acceptable to use the 90% acceptability limits when a higher standard of thermal comfort is desired."

[2] California's Title 24 Energy Code is among the most restrictive in the United States but its performance approach allows latitude in how tradeoffs are achieved. For reference, requirements are similar to Ashrae Standard 90.1. The base building used these recommended assemblies.

[3] ASHRAE Standard 62.1. Ventilation for Indoor Air Quality.

[4] ASHRAE Standard 55 adaptive comfort model assumes up to 0.3 m/s air motion. Air speeds higher than that, but no higher than 1.2 m/s, will extend the upper limits of the comfort zone according to the SET Method graphically represented in Figure 5.2.3.2. The 0.9 m/s difference between 0.3 and 1.2 m/s corresponds to 2.2°C of cooling.

REFERENCES

A.S.H.R.A.E. 2010. *ASHRAE Standard 55 – Thermal environmental conditions for human occupancy*. Atlanta, GA: American Society of Heating Refrigerating Air-Conditioning Engineers.

A.S.H.R.A.E. 2010. *ASHRAE Standard 90.1 – Energy standard for buildings except low-rise residential buildings.* Atlanta, GA: American Society of Heating Refrigerating Air-Conditioning Engineers.

A.S.H.R.A.E. 2010. *ASHRAE Standard 62.1 – Ventilation for acceptable indoor air quality*. Atlanta, GA: American Society of Heating Refrigerating Air-Conditioning Engineers.

Borgeson, S. & Brager, G. 2011. Comfort standards and variations in exceedance for mixed-mode buildings, *Building Research and Information* 39(2):118-133.

Carlucci, S. & Pagliano, L. 2012. A review of indices for the long-term evaluation of the general thermal comfort conditions in buildings, *Energy and Buildings* 53:194-205.

C.E.N. 2007. EN 15251 – Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, Brussels, Belgium: European Committee for Standardization.

de Dear, R. & Brager, G. 1998. Developing an adaptive model of thermal comfort and preference, *ASHRAE Transactions* 104 (1A) 145–167.

Douglas, S. et al.. PG&E Zero Net Energy Pilot Program, Stage 1B Final Report. 2012.

Fanger P.O. 1967. Calculation of thermal comfort: introduction of a basic comfort equation, *ASHRE Transactions* 73 (2).

McGilligana, C., Natarajana, S. & Nikolopouloub, M. 2011. Adaptive Comfort Degree-Days: A metric to compare adaptive comfort standards and estimate changes in energy consumption for future UK climates, *Energy and Buildings* 43:2767-2778.

Nicol, J. & Wilson, M. 2011. A critique of European Standard EN 15251 strengths, weaknesses and lesson for future standards, *Building Research & Information* 39: 183–193.

Nicol, J. & Humphreys, M. 2002. Adaptive thermal comfort and sustainable thermal standards for buildings, *Energy and Buildings* 34:563-572.

Rohles, F., Hayter, R., Milliken, G. 1975. Effective temperature (ET*) as a predictor of thermal comfort, *ASHRAE Transactions* 81 (2) 148.

ACKNOWLEDGEMENTS

Several people have contributed to this research in special ways. Thanks to Ibone Santiago and Santosh Philip for sharing their knowledge and experience with thermal simulation. Thanks to Gail Brager and Sam Borgeson for their patient explanations of their comfort research. Thanks to our clients for giving us the opportunity to work on and learn from a diverse range of projects over the years.