Assessing the Triple Bottom Line of Alternative Window to Wall Ratios as Resilient Adaptations in Office Buildings

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ABSTRACT

The substantial effect of buildings on the economy, environment, and their occupants are increasingly well documented. The United Nations Environment Programme estimates buildings account for 30% of global raw material use, 25% of solid waste generation, 25% of water use, 12% of land use, and 33% of greenhouse gas emissions, the later mostly related to operational energy. Economically, buildings require significant financial resources to design, construct, and operate. Socially, the quality of the built environment directly affects human well-being as people in industrialized countries spend most of their time indoors. Consequently, assessing building design strategies from a triple bottom line perspective is essential.

The proportion of glazing in a building's envelope—the window to wall ratio (WWR)—influences many aspects of building performance over its life cycle, including material use, MEP design, and energy consumption. Reducing the WWR has also been studied as a resilient building strategy, with a goal of protecting the façade by increasing elasticity during relative displacements, protecting against windborne debris, and preventing air and water intrusion. Furthermore, WWR is a fundamental design decision affecting the comfort and satisfaction of building occupants, not to mention aesthetics.

Environmental, economic, and social effects of various WWRs were studied using prototypical building simulations. Building information models of the DOE's large office prototype were developed to perform Life Cycle Assessments (LCA) and investigate the implications of varying WWRs on environment impacts, life cycle cost, and occupant comfort. Preliminary results suggest that reducing the WWR decreases operational energy, reduces most LCA impact categories, while moderating thermal discomfort, and glare risk. However, tradeoffs between upfront and operating costs, and reduced daylight autonomy, must be considered.

INTRODUCTION

Windows are one of the most important components of a commercial envelope system, which is in turn critical to the long-term performance of buildings and can influence a wide range of environmental, economic, and social impacts (Tucker 2015; Haglund 2010; Granadeiro et al. 2013). In 2016, approximately 19% of the total US primary energy consumption was attributed to the commercial building sector, which amounted to some 17.5% of the nation's carbon dioxide (CO2) emissions (U.S. Energy Information Administration 2018). An estimated 34% of commercial building energy use is window-related, including energy for lighting, heating, and cooling (Apte and Arasteh 2008) meaning that windows in commercial building are responsible for about 6,200 trillion Btus of energy use and 310 million metric tons of CO2 equivalent emissions. Economically, the total US construction sector (including non-buildings, but not design or operations) amounted to $792.5 billion in 2016, or 4.3% of GDP. The exterior envelope

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(including windows) is a substantial portion of the cost of commercial construction. In multi-story offices it "may even exceed 20% of the total building construction cost" (Arnold 2016). Notwithstanding the age of the study, the widely-quoted statistic that Americans spend some 87% of their day inside buildings (Klepeis et al. 2001) makes clear that humans are now an indoor species; that building interiors are the primary environment affecting social and personal wellbeing. This interior existence magnifies the importance of fenestration; and the light, view, air and connection it provides to the outside world.

The proportion of glazing in a building's envelope—described using the almost tautologically-simple metric of window to wall ratio (WWR)—represents an important design concern with wide-ranging consequences. Among other things, WWR directly affects the thermal performance of the envelope, the amount and frequency of useful daylight (i.e. daylight illuminance and daylight autonomy) and the associated human thermal and visual comfort (Goia 2016). Because glazing conducts dramatically more heat than even modestly-insulted opaque wall assemblies, energy codes may limit the extent of glazing to reduce conductive gains and losses through the envelope. Furthermore, in commercial buildings, increased window area may admit undesirable solar gains, contributing to larger peak loads. For example, the model code of ASHRAE Standard 90.1 limits the overall building WWR to 40%, with the glazing properties established based on climate (ASHRAE 2016).

Because of these important implications, significant prior work has sought to optimize WWR through various quantitative methods (Mangkuto, Rohmah, and Asri 2016; Goia 2016; Kasinalis et al. 2014; Goia, Haase, and Perino 2013; Leskovar and Premrov 2011; Didwania, Garg, and Mathur 2011; Ghisi and Tinker 2005; Inanici and Demirbilek 2000). Selecting an objective function which addresses the many consequences of WWR presents a serious challenge for optimization, and many studies simplify to a single objective such as minimum operating energy.

Single objectives, however, are poor metrics for sustainability. Seeking to cast issues of sustainability in language familiar to business, Elkington proposed the idea of a *Triple Bottom Line* (TBL) that accounted for the social and environmental as well as the economic consequences of decisions (2004). Now sometimes described with the alliterative *people, planet, and profit*, TBL aspires to a more comprehensive and holistic assessment than the isolated metrics and thresholds represented by typical building standards, rating systems, and codes. TBL is well-suited to analyze the multifarious implications of WWR, and some prior work has been done in this direction (Su and Zhang 2010). The present study uses multiple methods to understand the implications of differing WWR for each of the three "bottom lines".

Life cycle assessment (LCA) is a method to tabulate the environmental impacts associated with the inputs and outputs of a product or system over the expected life cycle, from raw material extraction to disposal (ISO 14040 1997). As a comprehensive approach to environmental sustainability, LCA methods have been applied to individual materials and processes, as well as to whole buildings (Quale et al. 2012; Junnila, Horvath, and Guggemos 2006).

Life Cycle Cost (LCC) assessment grows out of conventional accounting methods to assess building financial performance over time. These approaches are increasingly employed in conjunction with environmental analysis, for example to determine the payback or return on energy-saving investments, a particularly important consideration for the design of the exterior envelope (Islam et al. 2014).

The influence of building parameters on human comfort, satisfaction and productivity are areas of longstanding and significant research. The effects of windows, and lack of windows, have been studied for decades (Collins 1975; Larson 1965). A mature body of research explores the influence of thermal and visual comfort on learning (Baker and Bernstein 2012; Plympton, Conway, and Epstein 2000; Heschong Mahone Group 1999); productivity (Zhang et al. 2010; Kroner 2006; Boyce 2004); and health (Huisman et al. 2012; Ulrich 1992, 1984). Despite the robust research, identifying suitable metrics remains a challenge for work that seeks quantitative measures of buildings' effect on humans. Post-occupancy surveys offer valuable feedback once projects are completed (Frontczak et al. 2012), but in design, measurements of physical phenomena and their expected human consequences must often suffice.

In addition to its effects on energy use and occupant comfort, WWR also has important implications for the long-term usability and adaptability of buildings. In fact, WWR was selected for investigation after being observed to influence resilience and sustainability in contingent, rather than deterministic ways (Phillips et al. 2017). The WWR affects the seismic response of a structure, and larger WWR also increases the risk from windborne debris (Masters et al. 2010; Minor 2005, 1994) although quantitative tools to evaluate these resilience hazards and implications are currently limited.

METHOD

This study uses the Triple Bottom Line (TBL) approach to analyze the environmental, financial and social performance of a prototypical office building, while comparing a range of WWR configurations. Combining building energy modeling (BEM), environmental life cycle assessment (LCA), life cycle costing (LCC), and standard occupant comfort metrics, this TBL approach offers a holistic—although by no means exhaustive—comparison among buildings with differing WWR and locations.

Building Characteristics

We developed a Building Information Model (BIM) based on the geometric and other building properties of the prototypical buildings being studied. To support replication, we selected buildings from the Commercial Prototype Building Models developed by Pacific Northwest National Laboratory (PNNL) based on the DOE Commercial Reference Building Models (Deru et al. 2011). This suite of models represents 80% of the US building stock, across 16 building types in 17 locations. Prototypes are in the form of an input data file (IDF) for the EnergyPlus simulation engine, describing basic building geometry, materials, and system properties necessary for energy modeling. However, the prototypes exclude structural, systems, interior design, and physical representations of HVAC systems. A baseline BIM was constructed by translating the materials and geometry defined by the IDF into Autodesk Revit® software (*Revit* (version 2015) 2015), and developing missing elements based on conventional practices and engineering judgement. This complete BIM allows easy material takeoffs for the environmental LCA and economic analysis, while the original prototype energy model calculates operating energy values for the LCA, and provides measures of interior conditions for the comfort assessment.

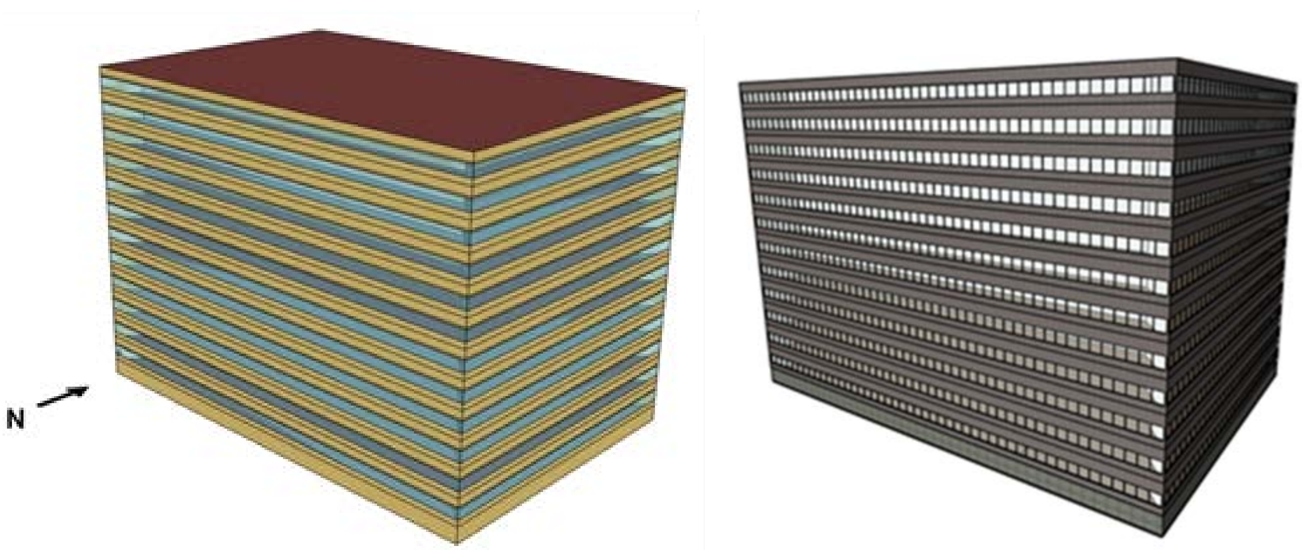

Figure 1: Images of the Prototype building in EnergyPlus (left) and the subsequent BIM (right), note windows.

Prototype Building. This paper focuses on the Large Office Prototype building, which is illustrated in Figure 1 and described below based on information from the Prototype Scorecard (2016). The Large Office measures 240x160 feet, has twelve stories above grade and a conditioned, below-grade basement, for a total of 498,600 square feet. The basement is eight-feet tall without a plenum, and consists of masonry walls and concrete slab floor. 28% of the basement is dedicated to a data center, and the prototype includes 12 traction elevators. Above grade floors have 13-foot floor-to-floor height including 9-foot ceilings, a 3.5-foot plenum, and a 6-inch concrete floor slab. The prototype's exterior walls are pre-cast concrete with insulation and gypsum wallboard, and experience a peak of 0.2016 cfm/sf infiltration. Ribbon windows are set with a 3-foot sill and 8.2-foot head height, resulting in 40% WWR evenly distributed on all four sides of the building. There is a built-up roof on metal deck.

The interior of the prototype is divided by uninsulated partition walls into four, 15-foot-deep perimeter thermal zones for each orientation, totaling approximately 29% of each floor by area, as well as a large central zone, and small (1% of the floor area) zone allocated for an IT closet. The area-weighted average occupant density is 194 sf per person, lighting power density at 1 W/sf, and plug and process power density at 1.661 W/sf. Schedules govern the occupancy, lighting, and plug loads, which is based on a five-day work week. The office zones are served with variable-air volume system with hot-water reheat, and data-center and IT zones by constant air volume systems. The central plant contains one gas-fired boiler and two centrifugal chillers for the offices, and the IT spaces are served by water source DX. Systems are auto-sized based on applicable codes and design day conditions.

The prototype served as the baseline for energy simulation in all climates. The information about form and materials included in the IDF also made it possible to design a concrete moment-frame structure and core for the building based on rules of thumb (Allen 2011), and those elements were incorporated into the BIM.

Window-to-Wall Ratio (WWR) Configurations. As mentioned above, the baseline office building achieves 40% WWR with continuous ribbon windows on all sides with a window height of 5.2 feet. Two additional ratios were studied, 20% and 60%, as shown in Figure 2. Reducing the WWR to 20% WWR while maintaining continuous strip windows would yield an unrealistically short (30-inch) window for a commercial building. Instead, the vertical dimensions of the baseline were maintained, and the area reduced in the horizontal direction with a series of evenly-spaced 5-foot-wide punched windows. On the other hand, the 9-foot ceiling height constrains the possible height for the increased WWR, so for 60%, the top of the window was set at the level of the plenum (9 feet above the floor) resulting in a sill height of 1.2 feet. These changes were made in the BIM, and in modified IDF files for energy simulation.

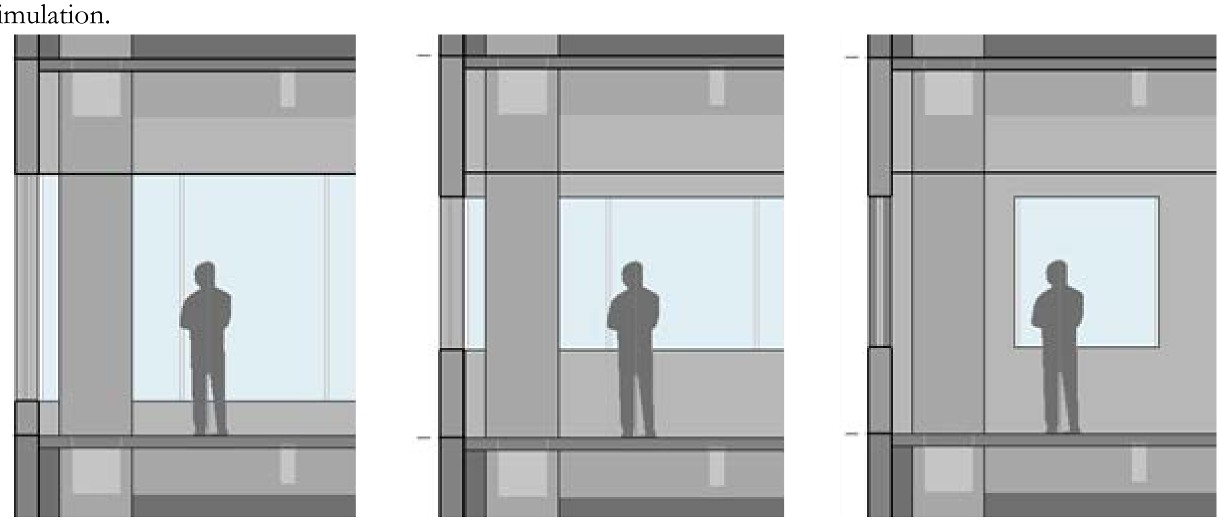

Figure 2: Interior elevations of WWR configurations. From left, 60%, 40%, and 20% WWR (image by authors).

Climate and Location. Prototype models are available for each building type in each of the eight ASHRAE US climate zones. To integrate with other ongoing work, this study evaluated buildings in three locations: Boston, San Francisco and Miami; representing zones 5A, 3C and 1A respectively. The material properties and component assemblies in the prototype models also vary by climate and reflect the requirements of local codes and standards. Wall and window thermal properties in the model, as well as mechanical equipment and other building components reflect the minimum requirements of ASHRAE Standard 90.1 (ASHRAE 2016). The default window and wall properties for each climate are shown in Table 1, and properties were held constant across WWR in the same climate. Each location is also associated with a TMY3 climate data file to provide hourly exterior conditions.

Table 1: Thermal and Visual Properties of Assemblies by Location

	ASHRAE Climate Zone		U-Factor (Btu/h-ft^2-°F)					Visual Properties	
			Roof		Walls			Glass	
Location	No.	Description	W Film	No film	W Film	No film	Glass	VT	SHGC
Boston, MA	5A	Cool Humid	0.032	0.033	0.090	0.097	0.418	0.444	0.397
San Francisco, CA	3C	Warm Marine	0.039	0.040	0.123	0.137	0.562	0.284	0.218
Miami	1A	Very Hot Humid	0.047	0.050	0.507	0.893	0.618	0.284	0.227

Environmental Assessment (Planet)

Life Cycle Assessment (LCA) was used to evaluate the ecological impacts of the materials, assemblies and accompanying processes required to construct and operate the building assuming a 60-year lifespan. The end-of-life phase is excluded from this LCA because the credit for recycling and reusing materials (e.g. aluminum) would disproportionally affect the results for some impact categories. We believe this is a reasonable limitation for a study focused on tradeoffs among WWR configurations, rather than on identifying the potential risk for burden shifting.

To streamline the LCA, we used Tally® (KT Innovations 2016), a plugin for Revit. Tally links elements in the BIM to appropriate material and process information, yielding not only a bill of materials, but a calculated Life Cycle Inventory (LCI) from which environmental impacts for each phase of a building's life are calculated. To compute these impacts, Tally uses a custom database of environmental impact categories developed using GaBi software, data and principles, and adjusts them based on project location. The Tally database is limited, and it is not possible to add custom assemblies or calculations. However, given that this study focused on the change in WWR, and other properties are held constant, we believe these constraints do not unduly affect the comparative outcome. We are currently evaluating the life cycle impact of WWR in relation to other building systems, such as mechanical system sizing, using manual methods. While the material impacts calculated by Tally dominate the construction stage, energy tends to dominate the operational stage. Operational energy was determined by simulating the prototype and modified IDFs using the EnergyPlus engine (*EnergyPlus* 2000), which were then combined with the Tally results for the complete LCA.

Economic Assessment (Profit)

The BIM provides an efficient way of quantifying each material, which is then mapped to appropriate cost data from RSMeans (Plotner 2016). RSMeans cost data is a widely-used reference throughout the AEC industry for standard and current cost information ("About RSMeans" 2018). Our BIM gives a list of approximately 25 specific materials, each is matched a unit cost that incudes materials and labor, and unit costs are simply multiplied by the quantity. In some cases (e.g. interior partitions) a blended unit cost accounts for complete assemblies, rather than individual materials. Given that WWR is the only variable, quantities (and associated costs) remained constant for many components, including major items such as the superstructure, roof, floors, and foundation. The first-cost elements affected by the different WWR configurations are the windows, opaque walls, and HVAC systems, while the operating cost changes are for electricity and natural gas. Annual energy consumption is reported from the EnergyPlus model, and applied over the 60-year building life. Windows were assumed to have a 40-year life, so the cost of replacement is included. Other components were assumed to either have the same life as the building, or to have identical replacement rates and costs regardless of WWR. Because this study is a comparative evaluation, costs were calculated in current dollars without discounting.

Human Comfort (People)

For the third leg of the TBL, we selected metrics of human comfort based on the WELL® Building Standard (Delos Living LLC 2014) to serve as proxies for the human and social implications of the varying WWR. We evaluated thermal comfort based on ASHRAE Standard 55 (2010), as quantified by the predicted percent dissatisfied (PPD). The modeled HVAC system is designed to meet this standard, and this value is calculated each hour by EnergyPlus for each thermal zone. In terms of visual comfort, we adopted two criteria, one based on sufficient *quantity* of light (maximum illuminance) and the other a measure of *qualitative* comfort (glare index.) While not a complete picture, these two metrics establish a framework for the luminous quality, and are relatively trivial to calculate with the existing models. Although not photometrically-accurate simulations of lighting, these results integrate directly with the energy consumption, LCA and LCC, an important consideration for this TBL evaluation. In this paper, we tabulated the annual hours in which the maximum daylight illuminance in each zone exceeds the setpoint for turning off the electric lighting. Similarly, we also report the hours each zone exceeds a threshold glare index: a measure of the relative brightness ratios within the visual field. We are currently developing more sophisticated evaluations of the effect of WWR on occupant comfort.

RESULTS

Energy Consumption

Total energy consumption was found to be directly correlated with WWR for all configurations and locations evaluated. Energy consumption of the prototype (40% WWR) was treated as a baseline, the change in source (primary) energy relative to that baseline for various end-uses are illustrated in Figure 1 for each climate. Note that several end-uses exhibit relatively slight changes across the various WWR, including humidification, heat recovery and heat rejection, so are displayed as 'Others' in Figure 1. The largest total change is the increase of almost 1,200 MBtu for 60% WWR in Boston. However, the change represents less than 1% difference from the baseline building. As shown in subsequent sections, while this results in only a minor change in the economic operating cost. the energy change is significant in evaluating the environmental impacts of building operations.

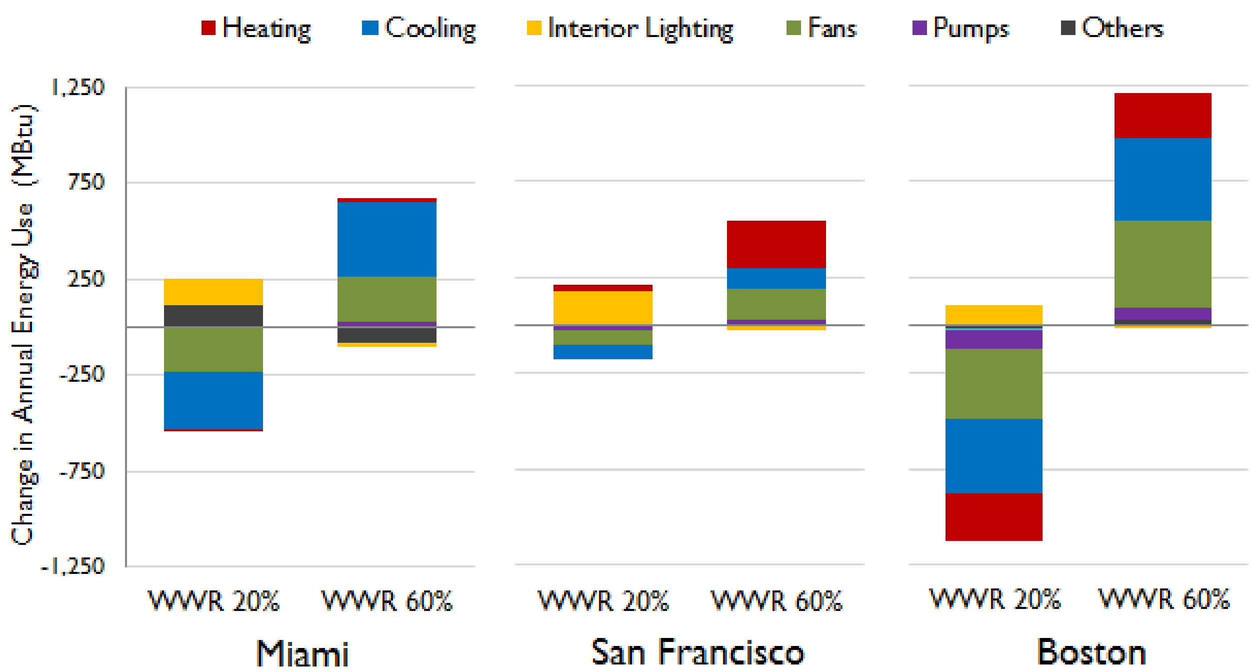

Figure 3: Source (primary) energy consumption by end use relative to 40% WWR baseline for each location. The 'Others' category is the sum of Humidification, Heat Recovery and Heat Rejection.

As expected, heating and cooling loads increased with larger WWR, as increased glazing area increases thermal conductivity, requiring more heating in winter/cool climates and more cooling in summer/warm climates. This finding held true for all WWR configurations tested in all three locations, except 20% WWR in San Francisco, which showed a slight increase in heating loads increased relative to the 40% baseline, likely because the reduction in solar gains outweighed the benefit increased thermal resistance in this mild climate. Similarly—given the design of the HVAC system—the positive correlation of WWR to fan energy, and the negative correlation with pump energy exhibited in all the configurations are consistent with expectations.

A negative correlation is expected between window size and interior lighting energy consumption, because smaller windows admit less daylight, reducing its ability offset for electric lighting, and indeed, the reduced WWR configurations do show notable increases in the lighting energy. Conversely, larger windows admit more daylight, however the reduction in energy consumption for the increased WWR is relatively small, perhaps because much of the added lighting occurs when the threshold for switching off electric lights would already be met by the baseline WWR, so the savings occur only at a relatively few marginal hours.

Life Cycle Assessment (Planet)

Operational energy dominates the other life cycle phases, as shown by the gray bars in Figure 4. These changes are illustrated relative to the baseline (40% WWR) building, and show operational energy dominates regardless of the direction of change. Although some of these changes are relatively small, that is in part because the total impact of the building is so large, and only the WWR is varying.

Across most impact categories considered, the total environmental impacts decrease with reduced WWR and increase with a larger WWR. Ozone depletion potential (ODP) is the only impact category that shows reduced impacts with increased WWR. Not coincidentally, ODP is also the only category in which the manufacturing phase (shown in red in Figure 4) has the largest contribution, likely do to the concrete in the pre-cast opaque wall.

As with operating energy (and because of it) 20% WWR configuration in San Francisco does not conform to the positive correlation for LCA impacts. Here, manufacturing is the largest phase in acidification potential (ACP) and both eutrophication potential (EUP) and smog formation potential (SFP) have maintenance and replacement as the greatest life cycle phase. Operations and manufacturing are equally significant in global warming potential (GWP).

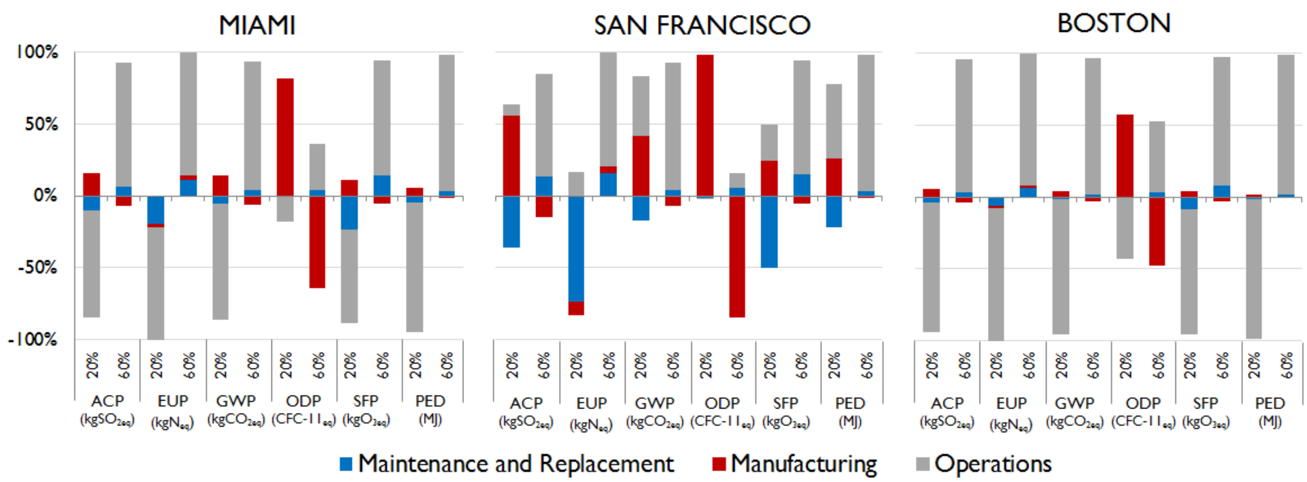

Figure 4: Environmental Life Cycle impacts relative to 40% WWR baseline for each location.

Life Cycle Cost (Profit)

For all three locations evaluated, the total project costs are positively correlated with WWR. As shown in Figure 5, the first costs for 20% WWR are less than the baseline, while the first costs for 60% WWR are greater. More significantly, in all cases the first costs are dominated by operating costs, particularly the cost of electricity over the life of the project. Based on these findings, we are reviewing alternative methods such as Net Present Value to discount future costs relative to first costs, and identify trade-offs for investment and expenditure.

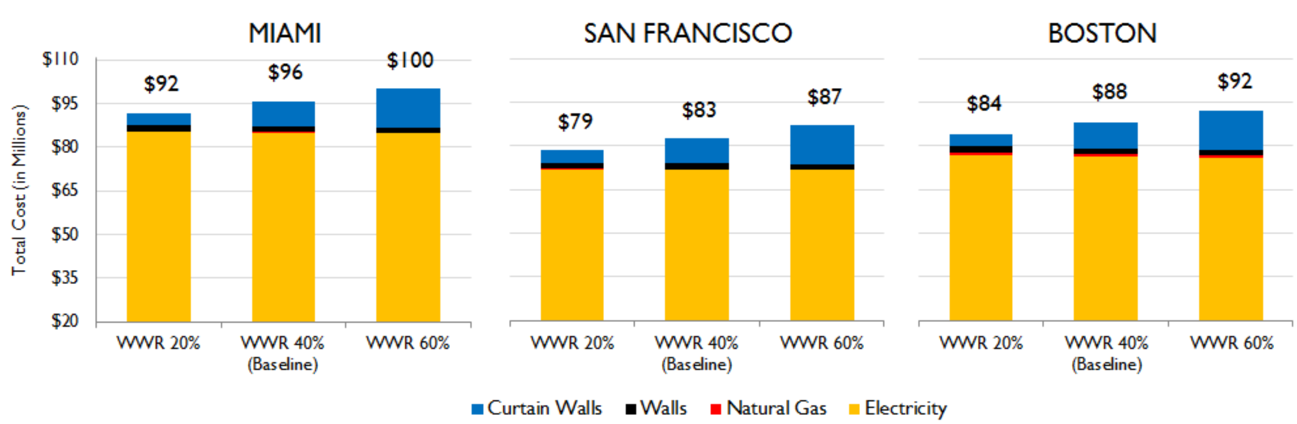

Figure 5: Total project cost in 2016 dollars for each WWR configuration and location over the 60-year life of the building.

Occupant Comfort (People)

As expected, increased WWR resulted in more hours exceeding the illuminance setpoint, while reduced WWR resulted in fewer hours exceeding the illuminance setpoint, a finding which held true across all orientations and for all building locations (Figure 6). These findings are consistent with the findings about lighting energy use discussed previously. Curiously, the hours exceeding the acceptable glare index increased for the smaller window (20% WWR) as well as the larger (60% WWR) for all orientations and locations. Because glare risk is a measure of relative brightness ratios in the visual field, we believe the dramatic increase at the 20% may be caused by the change from ribbon to punched windows, which juxtapose a bright window with an interior wall illuminated only by reflections. We are exploring alternative simulation methods and metrics for visual comfort to explore this finding.

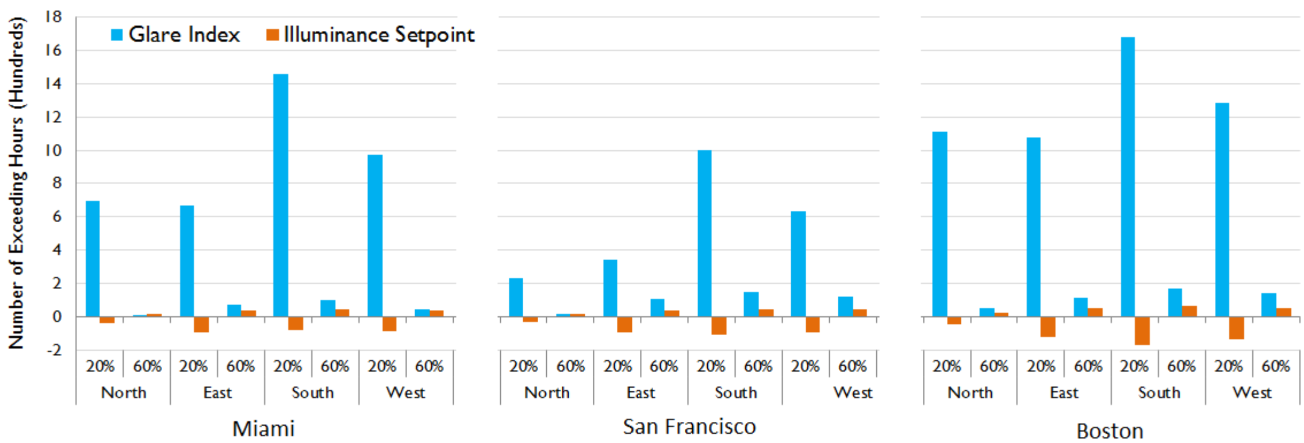

Figure 6: Change in annual hours exceeding the maximum allowable glare index and the illuminance setpoint relative to the 40% WWR baseline for each façade orientation and location.

The percent of the population dissatisfied with the thermal conditions was directly correlated to the WWR in all orientations of perimeter zone, and for all building locations (Figure 7). Surprisingly, the most dramatic changes occurred in San Francisco, which generally experiences the mildest climate among the three locations.

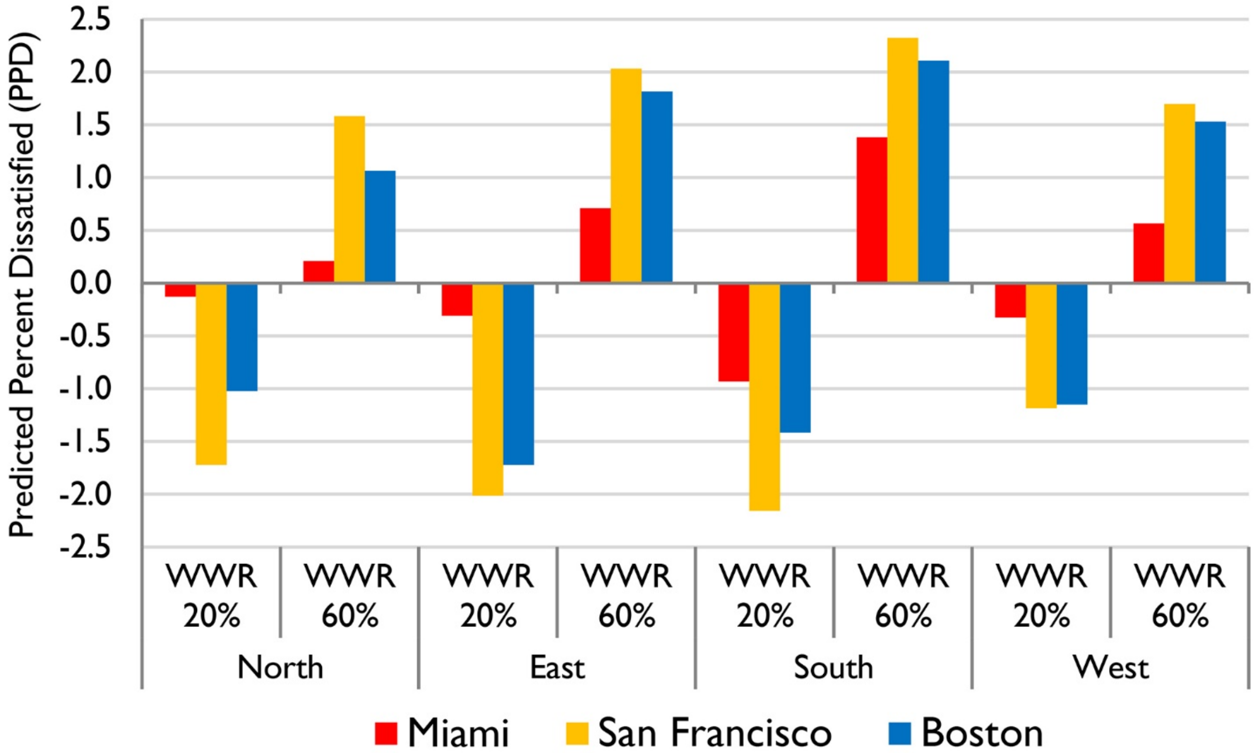

Figure 7: Change in the predicted Percent Population Dissatisfied (PPD) with the thermal conditions in the perimeter zone relative to those in same perimeter zone of the 40% WWR baseline for all locations.

Ongoing Work

This focused study considered only one building prototype, with three WWR, in three locations, so should not be extrapolated to general statements about WWR. We are increasing the resolution by simulating additional WWR, and broadening the application to additional climate regions. While the methods for LCA and LCC are robust, there are relatively few simulation-based metrics for building's contribution to social welfare. Even using human comfort as a proxy for social welfare limits the study to those quantifiable aspects which may be derived by simulation. Other metrics—particularly qualitative considerations—are difficult to capture in this methodology, but we believe that difficulty reveals more about the limits of the method than the optimal size for windows.

CONCLUSIONS

We applied a triple bottom line approach to evaluate the relative effect of specifying three different window-to-wall ratios on a large office prototype building in three climates. For this prototype, energy cost dominates construction cost over the life of the building regardless of WWR, and construction cost was positively correlated with increased WWR. For the three locations simulated, life cycle impacts were positively correlated with increased window area for most impact categories studied, and operational energy use dominates life cycle impacts. For this prototype, in the three locations simulated, daylight availability was positively correlated to increased window area, while thermal satisfaction was negatively correlated with increased window area. Glare risk was found to increase with both increases and reductions relative to the baseline of 40% WWR. While these results generally found lower WWR to have lower impacts across most aspects of a Triple Bottom Line assessment, they primarily point to the limitations of assessing building along just one dimension of sustainability metrics and/or in just one location. Examining multiple metrics reveals important trade-offs, such as increasing WWR leading to generally higher costs and greater environmental impacts, except for ozone depletion. Trade-offs among different sustainability dimensions are particularly important to consider as the various costs and impacts are felt by different stakeholders: economic construction costs by building owners, operational costs by tenants, social impacts by occupants, and environmental impacts by all building stakeholders, as well as society at large. This work highlights the need for a holistic approach to evaluate window to wall ratios, one considering multiple consequences, and prompts our ongoing work on finer-grained evaluations of WWR.

ACKNOWLEDGMENTS

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REFERENCES

"About RSMeans." 2018. Rsmeans.Com. 2018. https://www.rsmeans.com/info/contact/about-us.aspx.

Allen, Edward. 2011. *The Architect's Studio Companion Rules of Thumb for Preliminary Design*. 5th ed. Rules of Thumb for Preliminary Design. Hoboken, NJ: Hoboken, NJ : John Wiley & Sons.

Apte, Joshua, and Dariush Arasteh. 2008. "Window-Related Energy Consumption in the US Residential and Commercial Building Stock." LBNL-60146. Berkeley, CA: Lawrence Berkeley National Laboratory. https://facades.lbl.gov/sites/all/files/60146.pdf.

Arnold, Chris. 2016. "Building Envelope Design Guide." In *Whole Building Design Guide (WBDG)*. National Institute of Building Sciences. https://www.wbdg.org/guides-specifications/building-envelope-design-guide/building-envelope-design-guide-introduction.

ASHRAE. 2010. *Standard 55-2010: Thermal Environmental Conditions for Human Occupancy*. Atlanta, GA: ASHRAE.

———. 2016. *ANSI/ASHRAE/IES Standard 90.1: Energy Standard for Building except Low-Rise Residential Buildings*. I-P. Atlanta, GA: ASHRAE.

Baker, Lindsay, and Harvey Bernstein. 2012. "The Impact of School Buildings on Student Health and Performance: A Call for Research." McGraw-Hill Research Foundation. http://mcgraw-hillresearchfoundation.org/wp-content/uploads/2012/02/GreenSchoolsWP-2012.pdf.

Boyce, Peter. 2004. "Reviews of Technical Reports on Daylight and Productivity." Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute.

Collins, Belinda Lowenhaupt. 1975. "Windows and People: A Literature Survey, Psychological Reaction to Environments With and Without Windows." C 13.29/2:70. Washington: U.S. Dept. of Commerce, National Bureau of Standards.

Delos Living LLC. 2014. *WELL Building Standard*. 1.0. New York, NY, US. https://www.wellcertified.com/en/explore-standard.

Deru, Michael, Kristin Field, Daniel Studer, Kyle Benne, Brent Griffith, Paul Torcellini, Bing Liu, et al. 2011. "U.S. Department of Energy Commercial Reference Building Models of the National Building Stock." NREL/TP-5500-46861. Golden Colorado: NREL. https://www.nrel.gov/docs/fy11osti/46861.pdf.

Didwania, Srijan, Vishal Garg, and Jyotirmay Mathur. 2011. "Optimization of Window-Wall Ratio for Different Building Types." https://www.researchgate.net/profile/Srijan_Didwania/publication/259921312_OPTIMIZATION_OF_WINDOW-WALL_RATIO_FOR_DIFFERENT_BUILDING_TYPES/links/0c96052e8be7617c6e000000.pdf.

Elkington, John. 2004. "Enter the Tripple Bottom Line." In *The Triple Bottom Line, Does It All Add up? Assessing the Sustainability of Business and CSR*, edited by Adrian Henriques and Julie Richardson. London; Earthscan.

EnergyPlus. 2000. US Department of Energy.

Frontczak, M., S. Schiavon, J. Goins, E. Arens, H. Zhang, and P. Wargocki. 2012. "Quantitative Relationships between Occupant Satisfaction and Satisfaction Aspects of Indoor Environmental Quality and Building Design." *Indoor Air* 22 (2): 119–31. https://doi.org/10.1111/j.1600-0668.2011.00745.x.

Ghisi, Enedir, and John A. Tinker. 2005. "An Ideal Window Area Concept for Energy Efficient Integration of Daylight and Artificial Light in Buildings." *Building and Environment* 40 (1): 51–61. https://doi.org/10.1016/j.buildenv.2004.04.004.

Goia, Francesco. 2016. "Search for the Optimal Window-to-Wall Ratio in Office Buildings in Different European Climates and the Implications on Total Energy Saving Potential." *Solar Energy* 132 (July): 467–92. https://doi.org/10.1016/j.solener.2016.03.031.

Goia, Francesco, Matthias Haase, and Marco Perino. 2013. "Optimizing the Configuration of a Façade Module for Office Buildings by Means of Integrated Thermal and Lighting Simulations in a Total Energy Perspective." *Applied Energy* 108: 515–27. https://doi.org/10.1016/j.apenergy.2013.02.063.

Granadeiro, Vasco, José P. Duarte, João R. Correia, and Vítor M. S. Leal. 2013. "Building Envelope Shape Design in Early Stages of the Design Process: Integrating Architectural Design Systems and Energy Simulation." *Automation in Construction* 32 (July): 196–209. https://doi.org/10.1016/j.autcon.2012.12.003.

Haglund, Kerry L. 2010. "Decision-Making Methodology & Selection Tools for High-Performance Window Systems in US Climates." *BEST2, Strategic Issues in Building Design, WB13e4*. http://www.nibs.org/resource/resmgr/BEST/BEST2_052_WB13-4.pdf.

Heschong Mahone Group. 1999. "Daylighting in Schools: An Investigation into the Relationship Between Daylighting and Human Performance." Fair Oaks, CA: PG&E on Behalf of CEC PIER. http://www.centerforgreenschools.org/docs/heschong-mahone-daylighting-study.pdf.

Huisman, E. R. C. M., E. Morales, J. van Hoof, and H. S. M. Kort. 2012. "Healing Environment: A Review of the Impact of Physical Environmental Factors on Users." *Building and Environment* 58 (December): 70–80. https://doi.org/10.1016/j.buildenv.2012.06.016.

Inanici, Mehlika N, and F.Nur Demirbilek. 2000. "Thermal Performance Optimization of Building Aspect Ratio and South Window Size in Five Cities Having Different Climatic Characteristics of Turkey." *Building and Environment* 35 (1): 41–52. https://doi.org/10.1016/S0360-1323(99)00002-5.

Islam, Hamidul, Margaret Jollands, Sujeeva Setunge, Iftekhar Ahmed, and Nawshad Haque. 2014. "Life Cycle Assessment and Life Cycle Cost Implications of Wall Assemblages Designs." *Energy and Buildings* 84: 33–45. https://doi.org/10.1016/j.enbuild.2014.07.041.

ISO 14040. 1997. *ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework*. International Standard Organization.

Junnila, Seppo, Arpad Horvath, and Angela Acree Guggemos. 2006. "Life-Cycle Assessment of Office Buildings in Europe and the United States." *Journal of Infrastructure Systems* 12 (1): 10–17. https://doi.org/10.1061/(ASCE)1076-0342(2006)12:1(10).

Kasinalis, C., R.C.G.M. Loonen, D. Cóstola, and J.L.M. Hensen. 2014. "Framework for Assessing the Performance Potential of Seasonally Adaptable Facades Using Multi-Objective Optimization." *Energy and Buildings* 79: 106–13. https://doi.org/10.1016/j.enbuild.2014.04.045.

Klepeis, Neil E., William C. Nelson, Wayne R. Ott, John P. Robinson, Andy M. Tsang, Paul Switzer, Joseph V. Behar, Stephen C. Hern, and William H. Engelmann. 2001. "The National Human Activity Pattern Survey (NHAPS): A Resource for Assessing Exposure to Environmental Pollutants." *Journal of Exposure Science and Environmental Epidemiology* 11 (3): 231–52. https://doi.org/10.1038/sj.jea.7500165.

Kroner, Walter M. 2006. "Employee Productivity and the Intelligent Workplace." In *Creating the Productive Workplace*, edited by Derek Clements-Croome, 2nd Ed., 348–56. London: Taylor & Francis.

KT Innovations. 2016. *Tally* (version 2016). KT Innovations. http://choosetally.com/.

Larson, C.T, ed. 1965. *The Effect of Windowless Classrooms on Elementary School Children: An Environmental Case Study*. Architectural Research Laboratory, Dept. of Architecture, University of Michigan.

Leskovar, Vesna Žegarac, and Miroslav Premrov. 2011. "An Approach in Architectural Design of Energy-Efficient Timber Buildings with a Focus on the Optimal Glazing Size in the South-Oriented Façade." *Energy and Buildings* 43 (12): 3410–18. https://doi.org/10.1016/j.enbuild.2011.09.003.

Mangkuto, Rizki A., Mardliyahtur Rohmah, and Anindya Dian Asri. 2016. "Design Optimisation for Window Size, Orientation, and Wall Reflectance with Regard to Various Daylight Metrics and Lighting Energy Demand: A Case Study of Buildings in the Tropics." *Applied Energy* 164 (February): 211–19. https://doi.org/10.1016/j.apenergy.2015.11.046.

Masters, Forrest J., Kurtis R. Gurley, Nirav Shah, and George Fernandez. 2010. "The Vulnerability of Residential Window Glass to Lightweight Windborne Debris." *Engineering Structures* 32 (4): 911–21. https://doi.org/10.1016/j.engstruct.2009.12.016.

Minor, Joseph E. 1994. "Windborne Debris and the Building Envelope." *Journal of Wind Engineering and Industrial Aerodynamics* 53 (1): 207–27. https://doi.org/10.1016/0167-6105(94)90027-2.

———. 2005. "Lessons Learned from Failures of the Building Envelope in Windstorms." *Journal of Architectural Engineering* 11 (1): 10–13. https://doi.org/10.1061/(ASCE)1076-0431(2005)11:1(10).

Phillips, Robert, Luke Troup, David Fannon, and Matthew J. Eckelman. 2017. "Do Resilient and Sustainable Design Strategies Conflict in Commercial Buildings? A Critical Analysis of Existing Resilient Building Frameworks and Their Sustainability Implications." *Energy and Buildings* 146 (July): 295–311. https://doi.org/10.1016/j.enbuild.2017.04.009.

Plotner, Stephen C., ed. 2016. *Building Construction Cost Data*. 74th ed. R.S. Means Company.

Plympton, Patricia, Susan Conway, and Kyra Epstein. 2000. "Daylighting in Schools: Improving Student Performance and Health at a Price Schools Can Afford." In *PROCEEDINGS OF THE SOLAR CONFERENCE*, 487--492. Madison. http://scholar.google.com/scholar.bib?q=info:mZtOA7NbBxMJ:scholar.google.com/&output=citation&hl=en&as_sdt=0,33&ct=citation&cd=0.

PNNL. 2016. "Large Office Prototype Model Scorecard." Pacific Northwest National Laboratory (PNNL). https://www.energycodes.gov/sites/default/files/documents/PNNL_Scorecard_Prototypes_Office_Large.xls.

Quale, John, Matthew J. Eckelman, Kyle W. Williams, Greg Sloditskie, and Julie B. Zimmerman. 2012. "Construction Matters: Comparing Environmental Impacts of Building Modular and Conventional Homes in the United States." *Journal of Industrial Ecology* 16 (2): 243–53. https://doi.org/10.1111/j.1530-9290.2011.00424.x.

Revit (version 2015). 2015. Autodesk Inc.

Su, Xing, and Xu Zhang. 2010. "Environmental Performance Optimization of Window–wall Ratio for Different Window Type in Hot Summer and Cold Winter Zone in China Based on Life Cycle Assessment." *Energy and Buildings* 42 (2): 198–202. https://doi.org/10.1016/j.enbuild.2009.08.015.

Tucker, Lisa M. 2015. *Sustainable Building Systems and Construction for Designers*. Second edition. London ; New York: Fairchild Books, an Imprint of Bloomsbury Publishing Inc.

Ulrich, Roger. 1984. "View Through a Window May Influence Recovery from Surgery." *Science (New York, N.Y.)* 224 (May): 420–21. https://doi.org/10.1126/science.6143402.

———. 1992. "How Design Impacts Wellness." *The Healthcare Forum Journal* 35 (September): 20–25.

U.S. Energy Information Administration. 2018. "Monthly Energy Review - Energy Information Administration." January 2018. http://www.eia.gov/totalenergy/data/monthly/index.php.

Zhang, Hui, Edward Arens, DongEun Kim, Elena Buchberger, Fred Bauman, and Charlie Huizenga. 2010. "Comfort, Perceived Air Quality, and Work Performance in a Low-Power Task-Ambient Conditioning System." *Building and Environment* 45 (1): 29–39. https://doi.org/10.1016/j.buildenv.2009.02.016.