Dynamic Building Environment Dashboard: Spatial Simulation Data Visualization in Sustainable Design

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Abstract

When communicating the results of environmental building performance analysis, it is important to display resultant information in order (1) to be holistically understood and (2) to guide architectural design decisions. This article proposes a spatial dashboard of environmental performance data as a means to intuitively relate architectural form and performance and achieve the two goals above. The dashboard visualizes daylighting, natural ventilation, and thermal comfort information spatially localized throughout axonometric representations of buildings. Results can be customized by time of day, adding time as another analytical dimension in addition to space. Environmental data, normally hidden, is visually revealed in relation to architectural form. The dashboard enables intuitive design decisions to be made relative to performance measures across time and space.

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Introduction

This paper is concerned with a single question, “How should a design professional make decisions based on environmental performance information?” The question is not as simple as it may initially seem. Decision making is guided by both the presentation and availability of data (Doelling 2014), and the relationship between design and engineering disciplines will play a pivotal role in addressing the energy problem (Tsigkari et al. 2013). It is distressingly difficult to communicate the outcomes of exploratory environmental simulation in a variety of formats that both design and engineering disciplines can relate to. For example, in most whole-building energy model graphical user interfaces (GUI), results are displayed as graphs, which can either relate to the entire building performance or an individual thermal zone or room performance. It can be difficult to assess environmental conditions throughout a building based on this presentation of data when there are hundreds of spaces with their own unique thermal conditions. In contrast, daylighting simulation tools display results with a high degree of spatial specificity which allows an easy understanding of the relationship of spatial qualities to daylight propagation.

In essence, the default modes of data communication in environmental simulation GUIs are often too general or too specific. The presentation of results often focuses on total energy in a single number, energy utilization index (EUI). Often this is broken down by sources—such as electricity, gas and renewables—or by causes: envelope, solar heat gains, ventilation, or internal gains. Alternatively, environmental data can be communicated across a shorter duration (month, day, hour, sub-hour) to understand the seasonal or daily performance of a building. Both measures, an annual single number and temporal performance data, are useful for assessing a design's performance and establishing a detailed understanding of said performance. Figure 1 illustrates a typical visualization that compares heat gains and losses in a single living room space of one of the examples in this paper (see Figure 5). However, it is extremely difficult to understand the flows of energy, heat, air and light throughout a building based on such a graphs, because while it is very specific at the room level, such data makes it impossible for a user to comprehend the relationship between many rooms at once.

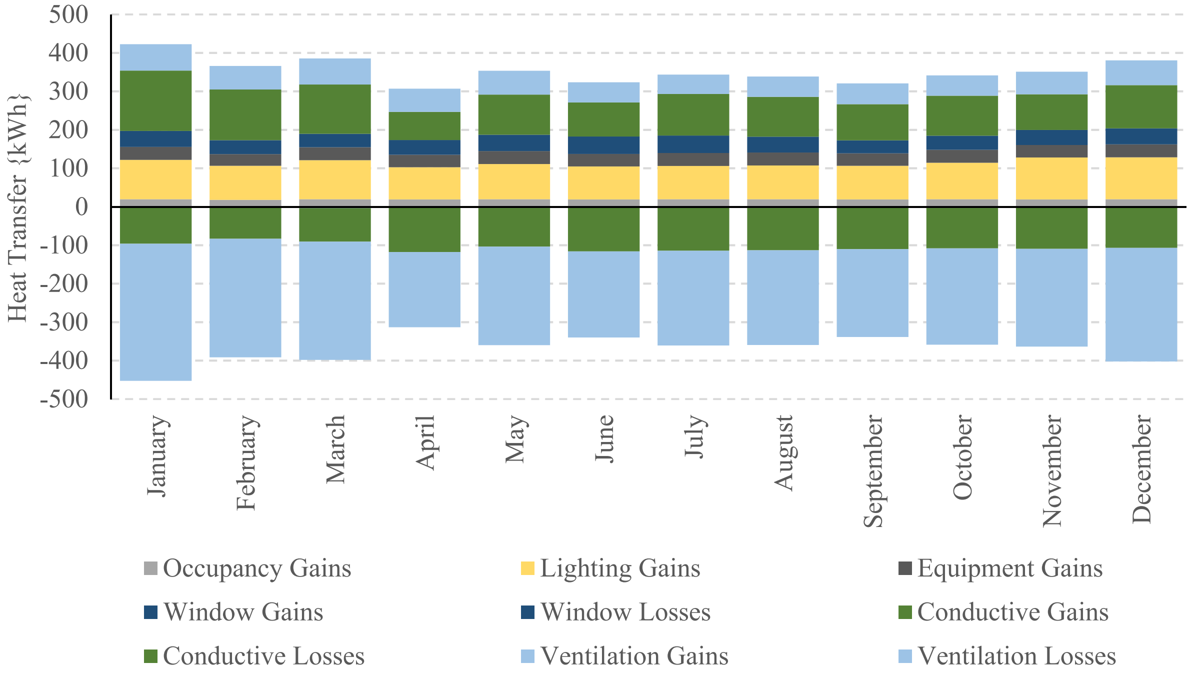


Figure 1. Monthly heat gains and losses for the living space of Villas en Bande (see Fig. 5)

This paper therefore proposes a workflow for the analysis of building performance results with an emphasis on spatial presentation and interaction with a myriad of environmental simulation results. Synergistic effects are explored depending on the properties of the displayed metrics ('what do they show?'), their spatial resolution ('where, and in what detail do they show it?'), and their temporal resolution ('What is the severity or frequency of the phenomenon under analysis?') First, advances and thinking on the relationship between environmental performance data, its communication, and design professionals are explored. Following this background review, a series of metrics and measures to assess ventilation, thermal comfort, and daylighting as well as a data organizational structure are defined and implemented in a new visualization tool. The proposed metrics and visualization schema are applied to the analysis and subsequent design iterations of two schemes for high-rise housing in Singapore. Finally, the discussion reflects on the potential of such tools to influence design, their practicality, current limitations, and future necessary developments.

Background and Literature Review

The choice of performance metrics and the presentation thereof has a significant impact on understanding of the total performance of a design and what factors lead to that performance. however, environmental representation is always imperfect, because buildings and their internal environments have no holistic representation due to their complexity (Doelling and Nasrollahi 2012). Vernacio and colleagues (2001) suggest that to connect building performance simulation outputs to 'designerly' understanding and thought processes, performance metrics must be synthesized in a way which can address specific design dilemmas such as internal layout, shading devices, openings, finishes, and material selections. Agostinho (2005) hypothesized that designers use visual and spatial representation as their prime mode of communication and basis for reasoning. Marsh (2004), in an early paper on the Ecotect software, supports this statement by suggesting that environmental performance data is more intuitively understood when visualized in a 3D model. Only by achieving understanding in a 'designerly' way, Marsh (2004) states, can environmental analysis drive a design process.

Chen (2004) further notes that architects desire a visual connection to a design's performance, and in airflow analysis this often takes the form of 'smart arrows' that indicate a presumed ventilation condition as a vector. Chen states in the same study that such arrow-based presumptions can be completely inaccurate; therefore, evidence-based methods are necessary in order to meaningfully impact the design. Malkawi and Srinivasan (2005) took the display of such spatial information data to an extreme by producing a virtual augmented reality environment in order to explore computational fluid dynamics (CFD) results. A similar process is often followed in daylighting design; however, the vectors drawn are more often representative of real solar angles in order to design shading against direct sunlight or to map the depth of light penetration into a space (DeKay 2013). It is however impossible to account for all solar angles, changes in weather conditions, and diffuse interreflections of light using such a methodology. On the other hand, most daylighting simulation interfaces display spatial illuminance-based information that provides designers with Chen's visual connection between architectural form and performance results. Unfortunately, thermal analysis interfaces predominantly make use of graph-based displays such as those shown in Figure 1 which do not provide a visual connection, although tools such as Honeybee (Sadeghipour, Pak and Smith 2013) and Archsim (Dogan 2016) allow spatial performance metrics to be mapped at the thermal zone level. Honeybee (Mackey 2015) can also perform spatial thermal comfort calculations based on air stratification models, view factors to surrounding surfaces, and radiant adjustment for direct solar access.

One aspect to be cognizant of when assessing the above discussion on intuitive, spatial performance measures is the choice of what is being represented through the selection of specific performance metrics. Daylight factor (DF) is the ratio of indoor to outdoor illuminance calculated under a CIE overcast sky; however, DF is a poor predictor of actual daylighting performance (Tregenza 1980). Point-in-time illuminance calculations illustrate a specific condition of lighting and are spatial; however, they hold the same challenges as drawing solar vectors—only one specific point in time is represented. Annual, climate-based daylighting metrics (CBDM) have found a great deal of success for their holistic representation of design performance over a long period of time (Reinhart, Mardaljevic and Rogers 2006; Mardaljevic 2006; Reinhart and Wienold 2011). CBDMs are based on an annual illuminance distribution generated from typical meteorological year (TMY) weather data and a climate-based sky model (Perez, Seals and Michalsky 1993). While many CBDMs exist, two are referenced here: Daylight Autonomy at 300 lx ($DA_{300\ lx}$) and Useful Daylight Illuminance (UDI). $DA_{300\ lx}$ quantifies the percentage of occupied hours in a year at a specific sensor point where daylight illuminance meets or exceeds 300 lx. It has been demonstrated that DA 300 lx values of greater-than or equal to 50% of occupied hours from 8 AM to 6 PM correlate subjectively to human perception of a daylit space (Reinhart and Weissman 2012; Reinhart, Rakha and Weissman 2014). UDI is a series of four metrics that account for categorical lighting levels over time: UDIf—fell short

(<100 lx), UDIs—supplemental (100 lx–299 lx), UDIa—autonomous (300 lx–3000 lx), and UDIe—exceeded (>3000 lx). $UDIa_{300\ lx–3000\ lx}$ relates the frequency with which daylight can completely replace electric lighting. $UDIe_{3000\ lx}$ relates the percentage of hours that exceed 3000 lx with the presumption that lighting levels exceeding 3000 lx indicate increased potential for glare and visual discomfort (Mardaljevic, et al. 2012).

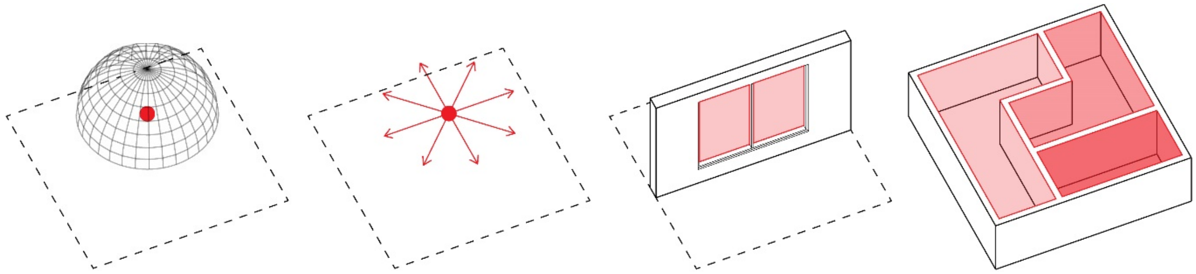
The climate-based daylighting metrics above pair very well with thermal simulation results, because thermal simulations are computationally based on transient heat flows using the same TMY weather data utilized in climate-based daylighting calculations (Crawley, et al. 2001). Therefore thermal results such as EUI, thermal comfort, and heat gains and losses are reasonable accompaniments to daylighting measures because they represent performance over the same period of time. In free-running, naturally ventilated buildings, the adaptive thermal comfort model (De Dear, et al. 1998) accounts for evidence that thermal comfort is a dynamic sensation relating to a rolling average of outdoor air temperature history. In air conditioned settings, the basic ASHRAE standard 55 (2013) model of comfort is preferred instead. As noted in the preceding paragraph, Mackey (2015) conceptualized a method of predicting spatialized comfort metrics based on Webb's (2012) previous work. This is especially beneficial, because thermal comfort information over a period of time can be conceptualized as a sister metric to $DA_{300\ lx}$ and UDI, thermal comfort autonomy (TCA). TCA represents the percentage of hours in a year where thermal comfort is achieved based on a specified comfort model. Ventilation information in terms of velocity and bulk air flow rates such as air changes per hour is also desirable in this context through detailed CFD simulations. Unfortunately CFD simulations are, at this moment, too time-consuming to make this practical in practice. The development of faster strategies for simulating annual CFD data is an active field (Wang and Malkawi 2015).

Returning to the idea of synthesis in a designerly context, several attempts have been made to the author's knowledge. Reinhart and Wienold (2011) proposed a dashboard view of simulation results that provides comprehensive information for a single-space 'shoebox' model on daylighting and shade operation, visual comfort, view, perimeter EUI, operation costs, and carbon emissions. Their analysis was focused on the impacts of daylighting on energy use in perimeter spaces and cannot be easily extended to entire buildings. Sustain (Greenberg, et al. 2013) is a private tool to display spatial and temporal data with a focus on designer understanding and ease of navigating large, parametric datasets. Doelling (2014) developed a tool to explore thermal and daylighting measures spatially based on a co-display of thermal results from EnergyPlus (Crawley, et al. 2001) and daylighting results from Radiance/Daysim (Reinhart and Walkenhorst 2001) simulation results. The tool, Mr. Comfy, allows interactive visualizations of a plethora of custom metrics over user-defined time scales. Doelling specifically focuses on designerly ways of understanding through spatial display of all building performance metrics either through sensor-based mapping (daylight) or thermal zone level mapping. This is especially evident as the Mr. Comfy tool began as a teaching tool for architectural studios at the Berlin Institute of Technology.

An Environmental-Spatial Dashboard

In this section, the authors present a means for communicating spatial building performance results using a suggested standard set of metrics and display scales in order to facilitate the understanding of the relationship between formal design and performance. The primary focus of this specific analysis is towards passive and human-centric measures such as thermal comfort, natural ventilation, and daylight illuminance; however, this analysis can be easily extended to relate to active thermal measures such as EUI, cooling loads, lighting loads, etc. Because the focus of this manuscript is on spatial understanding of building performance, an axonometric key drawing is always provided as a reference when displaying results with spatialized measures. The aim of such drawings, when paired with spatially related performance information, is to allow designers interacting with simulation results to understand the relationship of building form and environmental performance. In order to make these visualizations—such as those illustrated in Figures 5 and 7—extensions to the Mr. Comfy tool (Doelling 2014) were developed. The main additions discussed below are: (1) the development of a data structure for handling building performance information related to time, space, direction and physical values, (2) direct and automatic loading of EnergyPlus thermal simulation results into the Mr. Comfy visualization interface no matter the source interface, and (3) the addition of sensor-based thermal comfort calculations.

Any annual data set can be accepted by the tool as a conceptual 'zone,' which is derived from the thermal modelling term as it relates performance measures with a spatial component. Zones always contain 8,760 hours of performance results and can be a single point in space, a vector, a surface, or an air volume (a thermal zone). Annual performance data is required, because it facilitates a holistic understanding of performance across an annual weather cycle. This concept is illustrated in Figure 2 below with example measures that fit within each geometric type. For example, points can contain thermal comfort or climate-based daylighting information; vectors can contain visual comfort information; surfaces can contain information about heat gains, losses and volumetric air flows; and thermal zones can contain air psychrometric properties or energy use information. Disparate simulation results from thermal, ventilation and daylight performance are merged into a single display framework using the zone concept. Navigating, understanding and displaying complex data in this way becomes conceptually easier, because ordinarily separate performance data from different domains is organized, controlled and visualized from within the same interface.



Sensor Point
Thermal Comfort (ASHRAE 55, Adaptive Thermal Comfort)
Mean Radiant Temperature
Daylighting Climate-Based Illuminance (Daylight Autonomy, Useful Daylight Illuminance)

Vector
Visual Comfort (Daylight Glare Probability, Unified Glare Rating)
Vertical Illuminance

Surface
Solar Heat Gains
Volumetric Flow Rate
Surface Temperature
Heat Gains and Losses

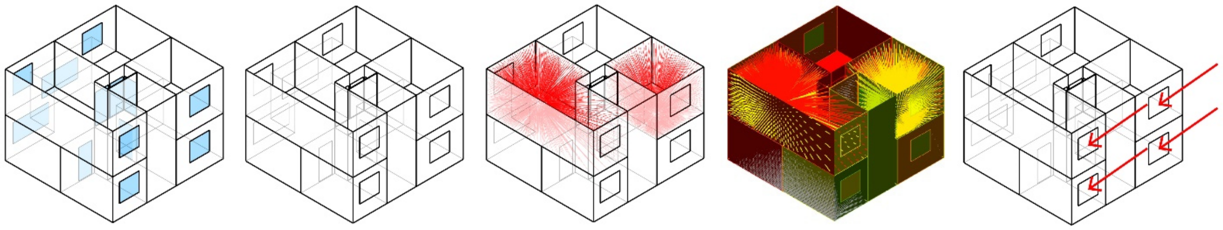
Thermal Zone
Air Temperature
Relative Humidity
Energy Use Intensity
Heating and Cooling Loads
Ventilation Rate (Air Changes per Hour, Volumetric Flow Rate)

Figure 2. Geometric zone types which can be understood in relation to representative annual performance information.

As inputs, the tool takes an EnergyPlus format IDF file and an ESO format results database (Crawley, et al. 2001). This information is automatically loaded into the Rhinoceros 3D/Grasshopper (McNeel 2015) interface. From the IDF file, walls, windows, floors, and ceilings are imported in a structured manner for three-dimensional display and remain associated with individual thermal zones from the energy model. External shading devices are also imported. From the ESO file, hourly performance data is imported and automatically associated with surfaces and thermal zones through automatic matching of field names. Optionally, this information can be translated into a daylight simulation model where annual, climate-based illuminance is calculated using Daysim (Reinhart and Walkenhorst 2001). Users may alternatively provide their own daylight simulation results. The primary utility of this method is that a user of any EnergyPlus interface may navigate their performance results in a three-dimensional, rather than graph-based, interface. A secondary benefit is that an energy model can be directly converted into a highly detailed lighting simulation model.

As noted previously, the spatialization of thermal comfort results is important, because it can be directly related to other spatial metrics such as daylighting. Differences in perception throughout a room can be understood relative to nearby surface temperatures and solar heat gains. The authors specifically choose to calculate and display thermal comfort autonomy (TCA) (Mackey 2015) using the ASHRAE standard 55 adaptive thermal comfort model 90% acceptance threshold (DeDear, et al. 1998). The steps involved in this process are documented visually in Figure 3. First, the thermal geometry and material properties are read in from the IDF file (3a). Then coincident wall surfaces are clipped from windows, and fronts and backs are slightly offset in order to avoid view collisions (3b). In this stage, the model is translated into the Radiance format (Ward 1994) and can be used for view factor or lighting calculations. Next, view factors are calculated between each sensor point in a grid and all surrounding building surfaces (3c).

Following that, hourly surface temperature results are paired with the view factor calculations in order to derive radiant temperature results (3d). Finally, direct solar calculations are used to derive a solar adjusted mean radiant temperature at each hour (3e). The entire process is transparent to the user, and TCA results are displayed as the percentage of total hours where comfort is maintained without the use of active air conditioning and mechanical ventilation systems. Areas with a TCA value below 35% are automatically colored pink in order to indicate overall undesirable thermal comfort conditions.



(a) Read thermal model geometry and material properties from IDF file

(b) Clip coincident walls from window surfaces for daylight or view factor analysis

(c) Calculate view factors from a sensor grid to every surface in the thermal model

(d) Derive hourly radiant temperature distribution from thermal results and view factors

(e) Adjust radiant temperatures based on hourly direct solar heat gain adjustments

Figure 3. Diagram of the calculation steps involved in spatializing radiant temperature results for TCA calculation across a sensor grid.

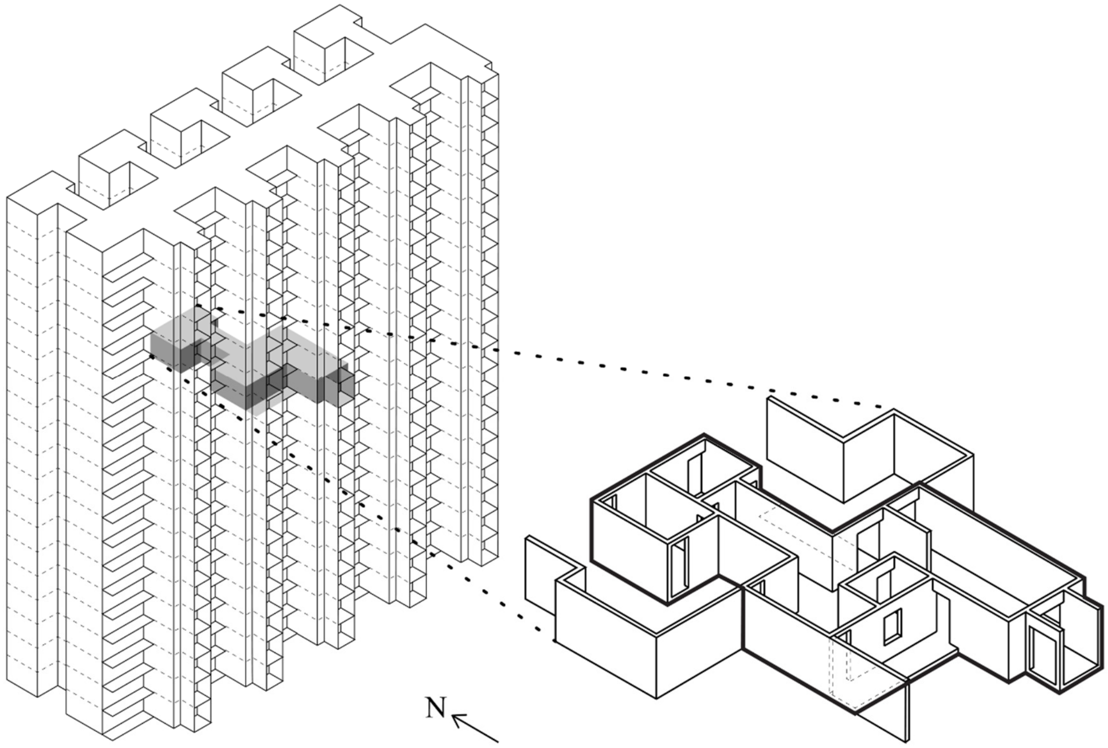
Daylighting results are visualized as the co-display of two metrics: $\mathrm{UDIa}_{300\,\mathrm{lx}-3000\,\mathrm{lx}}$ and $\mathrm{UDIe}_{3000\,\mathrm{lx}}$. $\mathrm{UDIa}_{300\,\mathrm{lx}-3000\,\mathrm{lx}}$ is selected as it approximately matches a lighting threshold that relates to human perception of what is daylit (Reinhart and Weissman 2012; Reinhart, Rakha and Weissman 2014) but also discounts excessive daylight. $\mathrm{UDIa}_{300\,\mathrm{lx}-3000\,\mathrm{lx}}$ is displayed on a scale ranging from 0 to 100% of occupied, daylit hours in the year (8am–6pm), and values of over 50% identify the daylit area. $\mathrm{UDIe}_{3000\,\mathrm{lx}}$ on the other hand identifies overlit areas that indicate increased potential for glare and visual discomfort (Mardaljevic, et al. 2012). Areas with a $\mathrm{UDIe}_{3000\,\mathrm{lx}}$ value greater than 15% of occupied hours are colored pink in order to indicate undesirable visual conditions and potential for excessive solar heat gains.

Ventilation information in this paper is calculated using the EnergyPlus airflow network (AFN) model (Walton 1989). The AFN is a simplified model for the prediction of bulk airflow rates throughout an architectural design based on pressures at node outlets and a series of linkages (windows, doors, grills, passages, etc.). It is capable of accurately calculating total volumetric airflow across openings and spaces; however, it is not capable of detailed air velocity and distribution information such as is found in CFD calculations. The choice of an AFN is because, as noted previously, it is computationally limiting at this time to generate enough CFD results in order to populate an annual spatial zone as described in this section. Ventilation results are visualized as average annual air change rates per hour (ACH). ACH represents the number of times air is replaced in a space each hour by fresh outdoor air due to leakage or intentional ventilation. In addition, the average annual velocity of air passing through windows while open is displayed as a surface output.

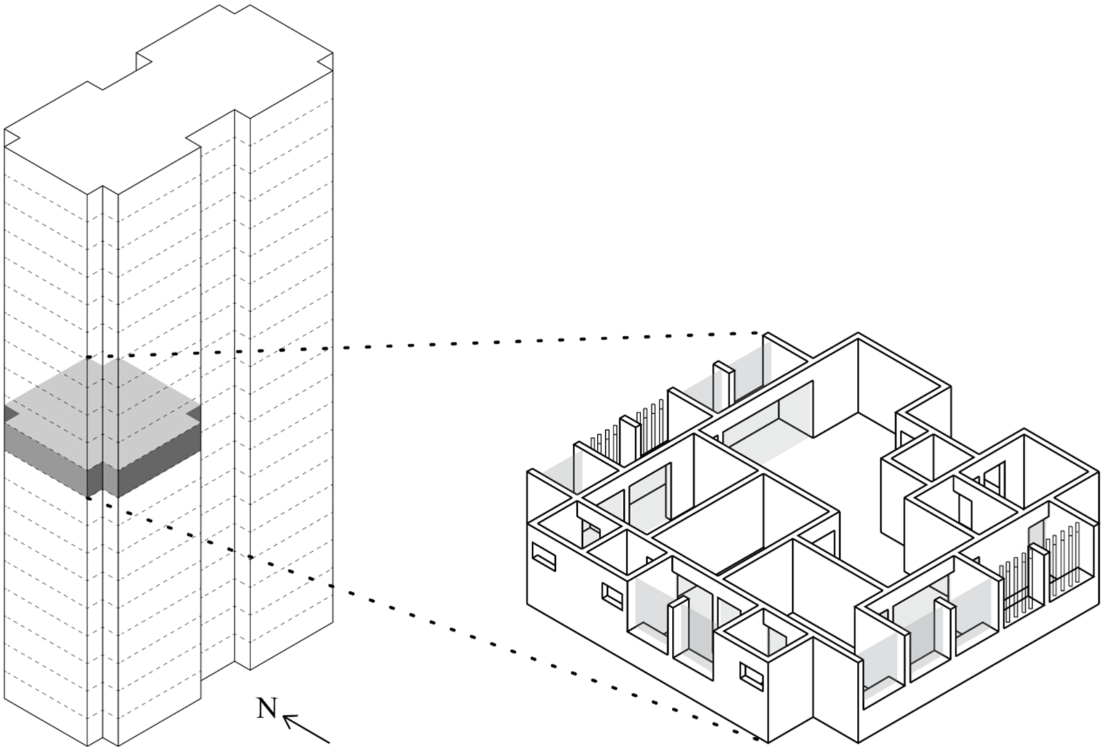
Design Explorations

Two example projects are examined for their passive potential in this manuscript, sourced from modernist designs for hot or hot and humid climates. The analysis performed is part of a larger project on passive architectural design in densifying tropical regions; therefore, all analysis is for a typical unit which may function as a stacked, highly dense aggregate. The design of the first project is based on Villas en Bande by the French-Moroccan architect Jean-François Zevaco. The analysed design translates his work into a high rise type, shown in Figure 4a. Villas en Bande is a design which aims to maximize surface area for heat exchange but minimize solar heat gains by a close aggregation forming miniscule courtyards on the North and South sides of the building. Windows and openings predominantly are shaded by overhangs or face inwards towards the courtyards. Spaces are always organized such that direct cross-ventilation is possible with windows on two sides, but windows are never oriented to view the neighboring units. The second project is based on DCM Apartments, an unrealized project designed by Charles Correa which is depicted in Figure 4b. The design of DCM Apartments emphasizes a buffering strategy and potential for natural ventilation. The perimeter of the plan is populated with shaded balconies, bathrooms, and the kitchen in order to reduce solar heat gains into critical spaces. A generous connected living and dining room spans across the design for ventilation during the day. Bedrooms are separated from the façade directly, always having a semi-enclosed balcony or bathroom serving as a thermal buffer.

All calculations herein are performed within the hot and humid Singaporean climate. The Singapore IWEC weather data is utilized within the EnergyPlus and Daysim simulation engines for this purpose. Simulations use a standard set of occupancy schedules and internal thermal loads derived from the UK National Calculation Method (Dept. for Communities and Local Government: London 2008). Specific materials are typical for the Singaporean region. Opaque walls have an U-value of 3.73 W/m^2-K and are constructed of thermally massive concrete. Windows have an U-value of 5.91 W/m^2-K and a shading coefficient of 0.496. Ceilings, floors, and abutting surfaces are maintained as adiabatic in order to assess the performance of a dwelling unit located in the middle of a high rise tower as illustrated in Figure 4.



(a) Design derived from Villas en Bande by Jean-François Zevaco. 1969, Agadir, Morocco.



(b) Design derived from DCM Apartments by Charles Correa, 1971, unbuilt.

Figure 4. Two designs for high-rise, tropical, passive architecture analysed in this paper.

The performance results for Villas en Bande are illustrated on the following page in Figure 5. The design is well-ventilated; average annual ACH values in primary occupied spaces range from 9.0 to 34.4. Only two spaces within the plan show significant thermal discomfort, the foyer which is almost completely unshaded by the sun and the kitchen which has the highest internal heat gains (30.3 W/m^2 while cooking) and the worst ventilation (9.0 average ACH). It is evident that the abutting walls and shaded courtyards have a noticeable impact on thermal comfort within the dwelling. The wall most exposed to solar irradiation on the south-east side of the dwelling is heated up during the day and results in reduced thermal comfort compared to areas adjacent to more shaded walls. Provision of natural light is lacking in the interior corridor and living spaces, while the bedrooms appear to receive ample light. Only 63% of the unit meets Reinhart, Rakha and Weissman's (2014) definition of daylit. No space other than the entry foyer is substantially overlit.

Natural daylighting is substantially lacking in the design of Villas En Bande. By providing few windows within the courtyard for reasons of privacy, daylight is reduced, and internal heat gains from artificial lighting are increased. In addition, the enclosed kitchen space is relatively uncomfortable thermally. The authors applied small design modifications with the intent of increasing daylight and to improve thermal comfort in the enclosed kitchen. These operations are diagrammed (in red color) and their results shown in Figure 6. North-facing glass windows in the living spaces were added in order to admit more diffuse light from the courtyards, windows with external privacy screens were added to the corridor, and an operable side-window was added to the enclosed kitchen to aid in its ventilation while cooking. It was found that additional windows did not improve autonomous daylight levels (> 300 lx) due to the intensely shaded nature of the courtyards, so that plot is not shown. Supplemental lighting level improvements over 150 lx were however noticeable. The additions significantly improved thermal comfort. Ventilation rates increased 28.9% in the enclosed kitchen and nearly 15% in other occupied spaces, which directly resulted in increased heat dissipation and improved comfort as seen in Figure 6's TCA plot.

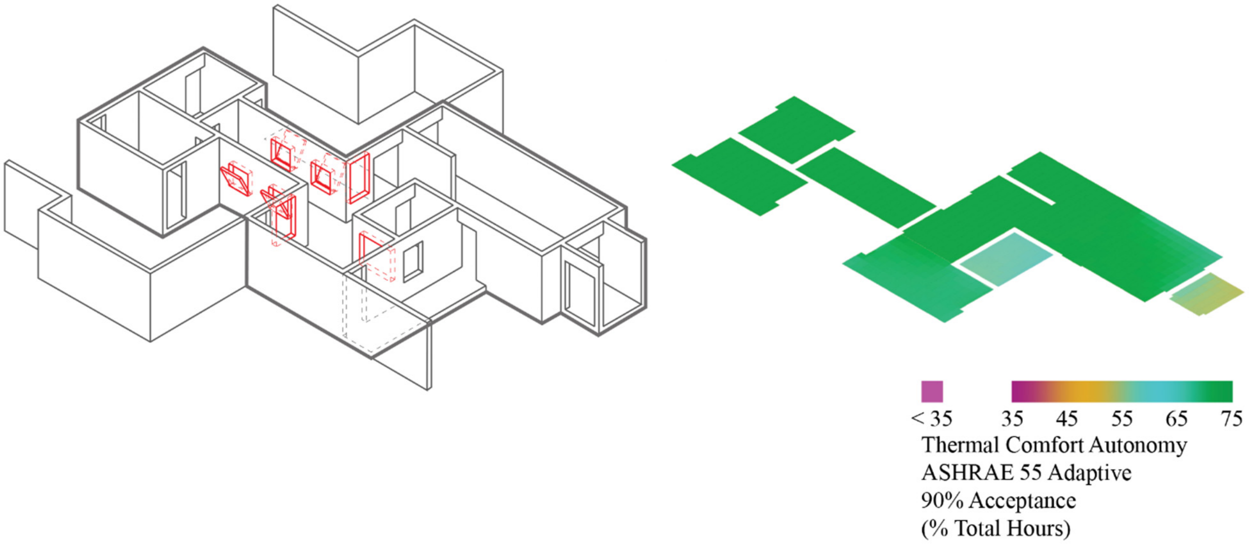


Figure 6. Design modifications (red) and updated thermal comfort results for Villas En Bande.

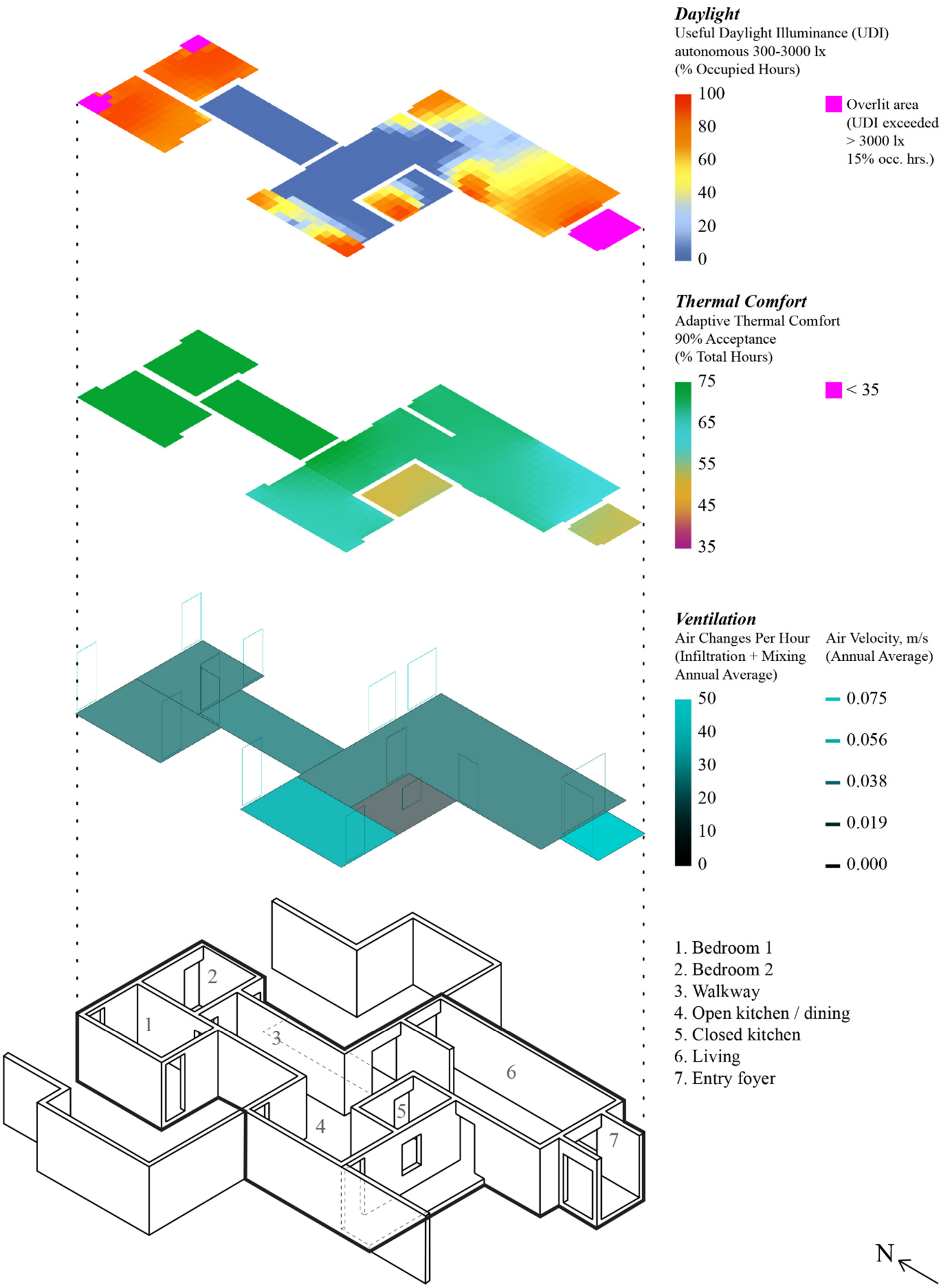
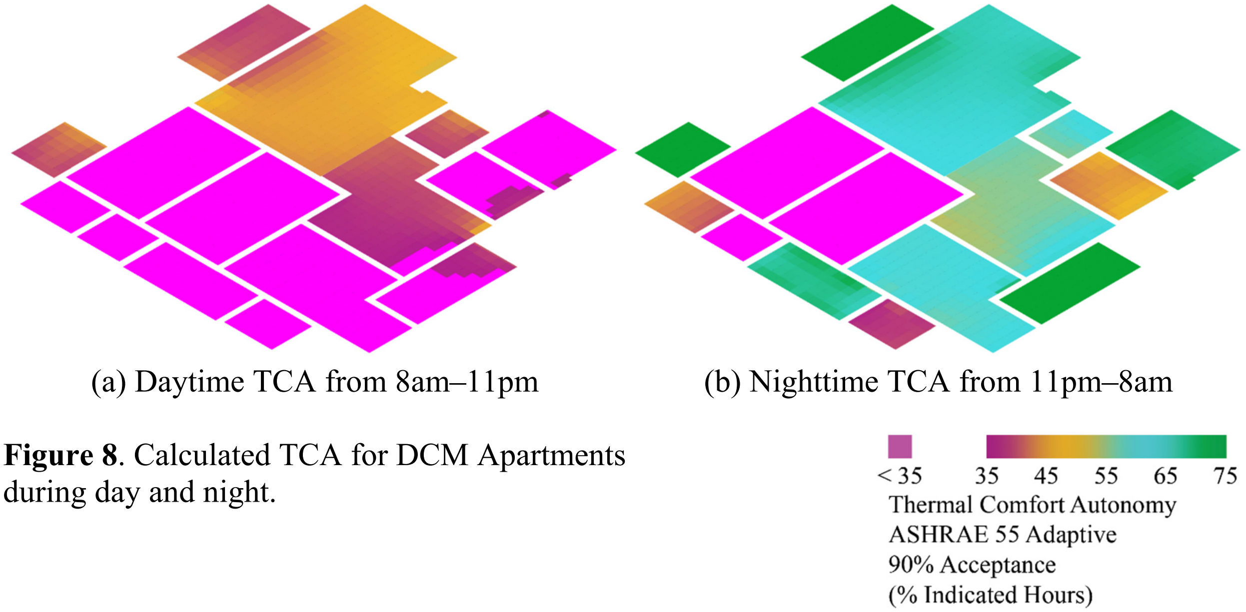


Figure 5. Dashboard results for Villas en Bande.

Performance results for DCM Apartments show that many of the main design concepts perform as intended, illustrated in Figure 7. Overlighting does not penetrate beyond the perimeter buffer zones, and 80.2% of the unit meets the definition of daylit. The living space which extends from the north-east to the southern portion of the unit is well-ventilated with an average annual ACH ranging from 19.0 to 32.6. However, ventilation rates in the bathrooms, bedrooms, and kitchen are less-optimal, ranging from 2.8 to 13.7 annual average ACH. This leads to thermal discomfort a substantial amount of the time. In the case of DCM Apartments, the authors additionally found it worthwhile to understand the thermal behavior of the building during day and night, because the time during which thermal comfort matters for a bedroom is at night, and by contrast thermal comfort is only important for living spaces during the day. Figure 8 portrays daytime TCA from 8am to 11pm (8a) and nighttime TCA from 11pm to 8am (8b). During daytime, the living space is the most comfortable in the unit, and perimeter spaces are less comfortable. The relatively higher ventilation rate in bedroom 3 as compared to bedrooms 1 and 2 is a substantial contributor to a pleasant thermal comfort level in the evening as there is a marked difference in overnight comfort levels between the three bedrooms.



(a) Daytime TCA from 8am–11pm

(b) Nighttime TCA from 11pm–8am

Figure 8. Calculated TCA for DCM Apartments during day and night.

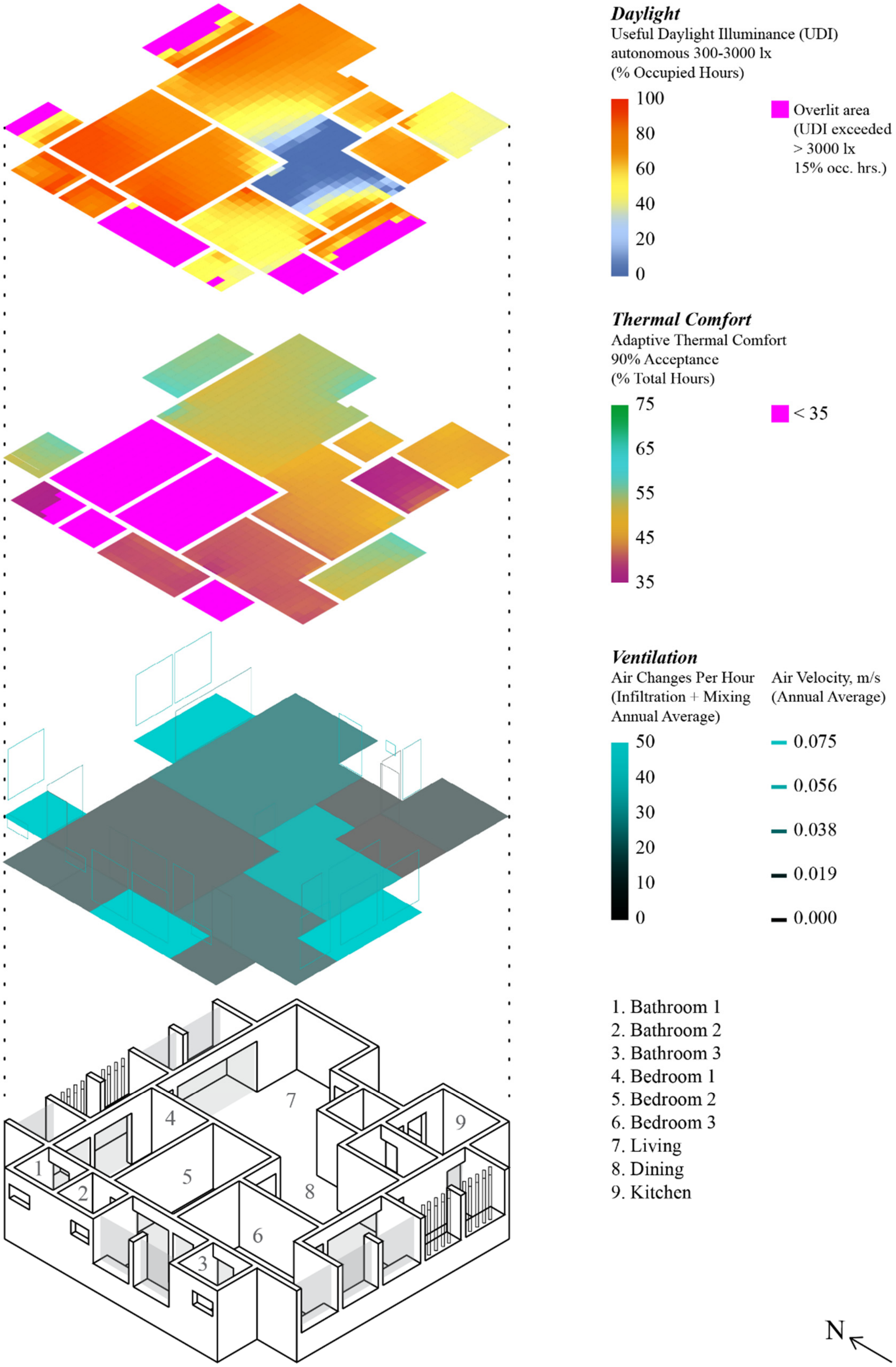


Figure 7. Dashboard results for DCM Apartments.

While overall DCM Apartments is well-lit, the two substantially thermally uncomfortable bedrooms could benefit from increased ventilation rates. In the case of bedroom 1, the northern side has high ventilation potential with two generous windows to a study space and a balcony respectively; however, the west side is only open to bathrooms with small windows. In the case of bedroom 2, cross-ventilation only occurs through a door to the living and dining space, and there may therefore be no good solution to improving ventilation without sacrificing privacy. In an attempt to increase ventilation to both bedrooms, the bathroom buffer spaces were reduced by one and redistributed along the west façade in order to provide primary ventilation access through open balcony spaces to each room. Figure 9 portrays this change isolated to the west side of the unit as well as resulting improvements in ventilation and thermal comfort. Significant improvement is noticeable in bedroom 1 while slightly improving bedroom 3. Bedroom 2, as hypothesized, does not improve beyond the 35% display threshold.

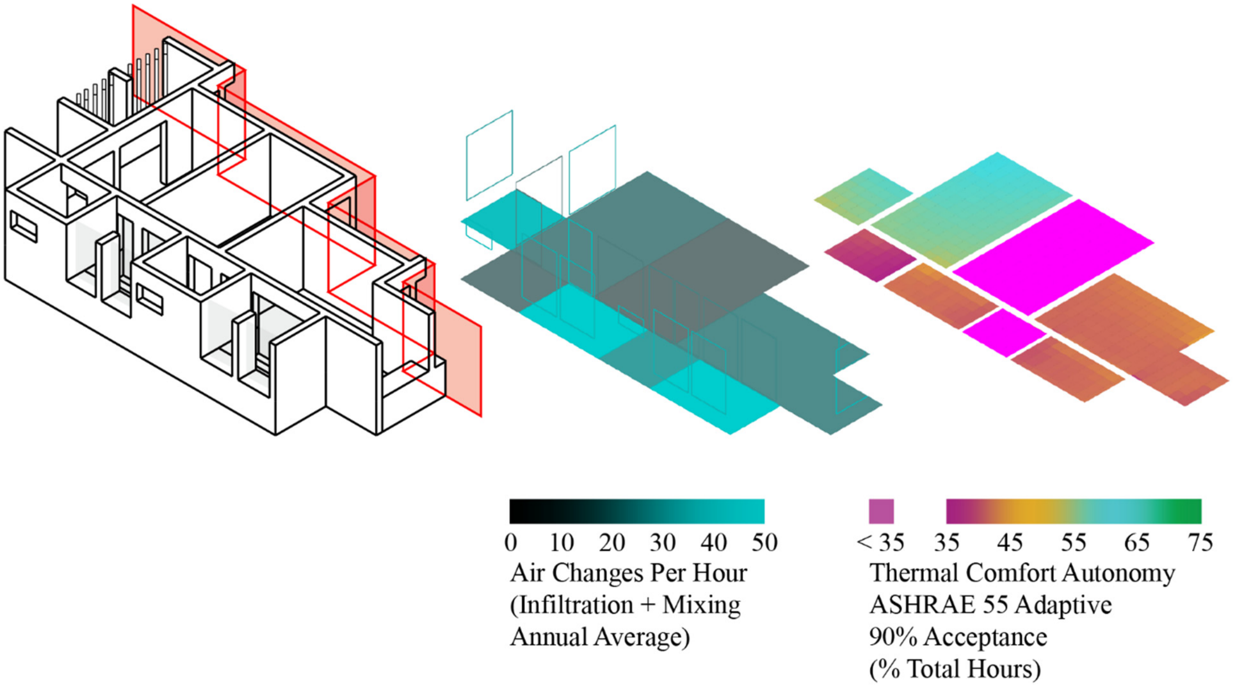


Figure 9. Ventilation rate and thermal comfort effects due to design changes along the West façade of DCM Apartments.

Discussion

This paper provides an overview of a schema to display and relate multiple spatial building performance metrics for passive design analysis. Three default metrics were proposed for this task: useful daylight illuminance, thermal comfort autonomy, and average ventilation rate as displayed in Figures 5 and 7. These metrics were chosen as they directly represent measures and benchmarks that a spatial designer may use in order to understand geometric effects. In terms of of spatial resolution, both zone-averaged (ACH) and sensor-based metrics (daylight, thermal comfort) were used together, as the air change rates directly influence the per-sensor reading of thermal comfort (TCA). The measures can be filtered by time as well in order to relate performance during different climatic circumstances (Figure 8). The schema is also directly expandable to metrics for buildings with active HVAC systems as it is integrated into a tool which can load any simulation measure with a spatial component at the sensor, vector, surface, or thermal zone level (Doelling 2014). This new schema can be seen as a full-building evolution of Reinhart and Wienold's (2011) daylighting dashboard. It shares the same aims of ease of access to complex performance data for experts and laymen alike. By making all measures spatial, the tool's aspiration is to foster intuitive understanding of the relation between building form and performance measures as well as to enable an easy integration into visual, architectural workflows. This section discusses the potential of the exhibited tool and other such tools to influence design, their practicality, current limitations, and future necessary developments.

Relevance to Design

The analysis methods presented herein display ventilation, thermal comfort, and daylight simultaneously and spatially using a single GUI. This information is particularly relevant for design professionals when trying to develop a building scheme that is passive in nature. For active buildings, EUI and other associated measures can be displayed. The authors believe that the selected metrics and display methods presented can be easily explained to laypeople while still exhibiting complex data in a designerly manner: "This pink colored part of the building is overlit," or "The dark-purple colored bedrooms are not very comfortable at night," or "Green colors indicate thermal comfort." The analysis presented herein also integrates easily within current workflows using EnergyPlus as the thermal simulation engine, which gives it the potential to immediately transform existing design workflows. Perhaps most importantly, different levels of holistic understanding are triggered by the referential nature of displaying three cross-domain measures simultaneously. Designers can interpret a single representation, but understanding is further shaped by seeing the synergistic or antagonistic relationships between sunlight, ventilation rate, thermal comfort and other measures.

Simulation Time and Effort

As with any tool, time and effort are important to consider in terms of its potential impact. In order to generate the spatially specific grid-based TCA and UDI measures, the simulation time was around 11 seconds per sensor on a single core 2.4 GHz processor, or about 4 hours for a single design iteration of around 1250 sensors, which is the analysis size of the DCM Apartments example. For quicker design iterations, the density of sensors can be reduced. The calculations also lend themselves to multi-core processing or GPU-based accelerations which could reduce the simulation time even further. Simulation effort is often a larger concern. Effort is also reduced by automatically converting a thermal simulation model into other useful performance domains (daylight, spatial thermal comfort) more information can be generated from a singular modelling action when most often designers must re-create daylight and thermal models in separate tools.

Limitations and Future Work

The potential of the zone organizational concept could be further explored. Means of displaying spatial visual comfort through vector zones is ongoing, although there are some existing references to learn from (Jakubiec and Reinart 2015; Ámundadóttir, Lockley and Andersen

2013). How users of the tool interact with temporal data through diurnal and seasonal differences also needs to be understood as design strategies in many climates rely upon understanding and reacting to such changes. A final, crucial hurdle for the building performance simulation community is the difficulty of assessing airflow throughout buildings on an annual basis. Direct knowledge as a vector zone geometry of air velocity and direction could have a significant impact on comfort; however, since this is computationally very difficult at this time, comfort is based purely on bulk airflow rates as a presumed 0.1 m/s air velocity. The authors look forward to a time in the future where CFD is as quick to perform as thermal and daylighting analysis.

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