A Spatial and Temporal Framework for Analysing Daylight, Comfort, Energy and Beyond in Conceptual Building Design

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Abstract

This manuscript describes a methodology for organizing and displaying disparate sources of building performance simulation data to form spatial displays of a myriad of building performance outputs and drive design understanding from an architectural point of view. The results are based on annual simulation data, are spatially discrete, and can be displayed and interpreted through a variety statistical methods. A series of simple visualizations to describe the performance of passive and active architectural design strategies are presented in addition to further suggestions for temporally varying data display animations.

Introduction

The building simulation community is increasingly generating greater amounts of raw data. This is most obvious when the number of discrete simulations is large as in the case of massively parametric calculations (Lagios, Niemasz, and Reinhart 2010; Samuelson, et al. 2016) or performance optimization simulations (Attia, et al. 2013; Nguyen, Reiter and Rigo 2014). It is less obvious that complex thermal, lighting, or fluid dynamics simulations produce staggering amounts of information within a single simulation model. This is due to the climatic, time-varying nature of the calculation (8760 hours / year), many spatial locations (sensor points) or the plethora of possible outputs. Building performance simulation (BPS) professionals and designers often hope to extract much more from an individual model than simple energy use intensity (EUI) to make intelligent design decisions. The vision of this paper is that designers and engineers should be able to learn as much as possible from these complex models through intelligent spatial and temporal data display and interaction with the results. To achieve this vision, careful attention must be paid to the reading, processing, interpretation and graphic display of BPS results.

Unfortunately, the default modes of data communication in environmental simulation graphical user interfaces often focus on total energy in a single whole-building number, EUI. This is sometimes broken down by energy sources—such as electricity, gas and renewables—or by heat transfer mechanisms: envelope conduction, solar heat gains, ventilation, internal gains, or air conditioning systems. Such methods are useful for assessing a design's performance and establishing a detailed understanding of said performance for an entire building or a single thermal zone. However, it is extremely difficult to understand the flows of energy, heat, air and light within a building based on predominantly numerical, tabular or graph-based outputs. While these outputs are very specific at a broad level (building) or a narrow focus (a single thermal zone), it is difficult for a designer to comprehend the relationship between formal design features, spatial qualities and the flow of energies throughout a building.

Architects and designers predominantly work with graphical data to make design decisions, especially in the early phases of the design process. Sketches and simple drawings provide direct feedback about the appearance and certain spatial qualities of a building in its entirety. BPS metrics should be equally capable of this type of graphical guidance to better support building designs from the conception and design development stages of a project. The authors propose that graphical communication of BPS results should meet the following goals,

(1) To be based upon annual, climate-specific BPS results; therefore, to align with current best-practice simulation methods in energy and daylight modelling.

(2) To be spatially and geometrically discrete as much as is possible so that performance is related to specific design features and spatial qualities.

(3) To enable navigation of performance results across different time scales and schedules such as hourly, daily and seasonally.

This paper details a technical approach to this data communication problem. Fundamentally, the authors propose a new method for how design or BPS professionals interface with a set of complex environmental data to drive design decisions. The authors propose methods for creating and displaying high quality BPS data starting from the common source of an EnergyPlus (Crawley 2011) input data file (IDF). Methods for displaying spatial energy, operative temperature, thermal comfort, daylighting, and natural ventilation at a high degree of spatial resolution are discussed. Finally, two types of standard building performance dashboards are suggested and prototyped—for passive and active, mechanically conditioned buildings. These new graphical, spatial and temporal outputs are intended to aid environmentally responsive passive design and low-energy building design in the future.

Review of Communication Methods

Representation of BPS outcomes 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 design 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; therefore, an intuitive visual representation is key. Marsh (2004), in an early paper on the Ecotect software, supports this statement by suggesting that environmental performance data is better understood when visualized in a 3D model. Associating BPS data with 3D geometry within the design environment, Marsh (2004) states, enables environmental analysis to drive a design process.

Chen (2004) notes that a visual connection to a design's performance is desirable for designers. In airflow analysis, this often takes the form of 'smart arrows' that indicate a presumed ventilation condition as a vector. Chen continues, stating that such arrow-based presumptions can be completely inaccurate; therefore, visual and evidence-based methods are necessary 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 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 to design shading against direct sunlight or to map the depth of direct light penetration into a space (DeKay and Brown 2013).

Thermal analysis interfaces predominantly make use of graph-based displays which do not provide a visual connection to the design of a space, 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 can also perform spatial thermal comfort calculations based on air stratification models, view factors to surrounding surfaces, and radiant adjustment for direct solar access (Mackey 2015).

CFD simulations by their nature produce spatialized BPS results for fluid flows, comfort, and thermal measures. Unfortunately, CFD simulations are, at this moment, too time-consuming to make annual simulations practical in practice. The development of faster strategies for simulating annual CFD outputs is an active field (Wang and Malkawi 2015).

Several attempts have been made to synthesize BPS information in a spatial manner. Reinhart and Wienold (2011) proposed a dashboard view of simulation results that provides comprehensive information for a perimeter-space 'shoebox' model on daylighting and shade operation, visual comfort, view, 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.

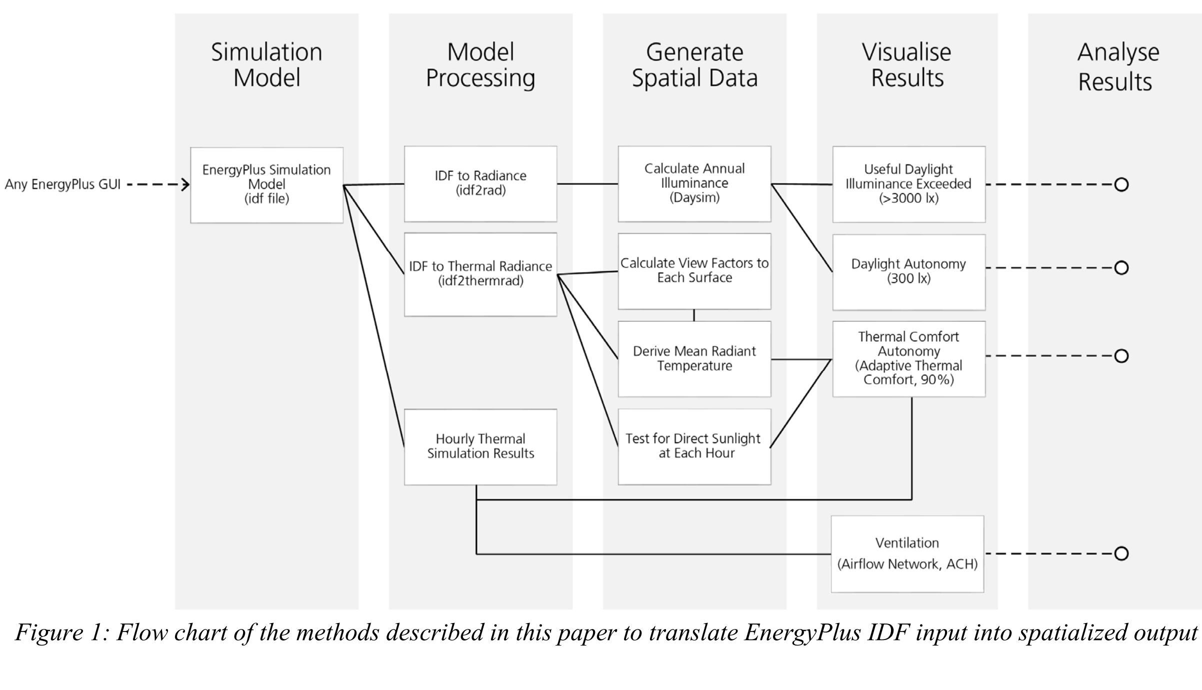


Figure 1: Flow chart of the methods described in this paper to translate EnergyPlus IDF input into spatialized output

Methodology for Spatial Performance Metric Communication

This section presents a computational process through which BPS data is created, organized, and displayed beginning from the EnergyPlus IDF format for multizone thermal building models. Spatialized thermal comfort and annual climate-based daylighting metrics are created and displayed across a grid of sensor points. In addition, every EnergyPlus zone or surface-level output can be displayed graphically overlaid on a building plan or 3D model. An overview of the process can be seen in Figure 1.

Processing IDFs into Daylight and MRT Models

An IDF file is read in by a simple, command-line tool to create Radiance format (Ward 1994) files for view factor, solar adjusted mean radiant temperature (MRT) calculations, and for annual climate-based daylighting measures. Each object in the IDF is stripped of white space, new lines, comment characters (`!`) and subsequent comments. Surface material properties are recorded from the `WindowMaterial:Glazing`, `WindowMaterial:SimpleGlazingSystem`, `Material` and `Material:NoMass` objects. Emissivity, visible absorptance, visible transmittance (Tvis) and solar heat gain coefficients (SHGC) are recorded for each material object. For each `Construction` object, the reflectance of the front and back surface materials are recorded, and from the `WindowConstruction` object, the combined Tvis is calculated by multiplying the values of all glazing layers in the construction.

Opaque and transmissive surface objects (`BuildingSurface:Detailed`, `FenestrationSurface:Detailed`, and `Shading:Building:Detailed`) are recorded based on their construction materials and the coplanar points defining their polygonal shape; however, transitioning from an IDF representation of a thermal model to a daylighting model, there are two major geometric issues to overcome: (1) windows within opaque surfaces are represented by two co-planar polygons, parent and child, without an explicit hole in the parent polygon through which light could pass, and (2) surfaces are infinitely thin. When calculating view factors for MRT calculation, another (3) issue is that the surfaces between two thermal zones are coplanar; therefore, it is difficult to separate the inside or outside faces of interior partition walls and internal floors. To solve the first problem, windows are treated as holes in wall surfaces. Figure 2 illustrates these changes graphically. A Delaunay triangulation algorithm (Shewchuk 1996) is used to triangulate the gaps while maintaining an open area for window surfaces to occupy. Regarding the second issue, utilizing infinitely thin surfaces rather than true volumetric representations of geometry can result in overpredicting daylight levels within a space (Ibarra and Reinhart 2009). The authors opted to apply a 0.8 reduction factor to account for mullions and a 0.8 reduction factor to account for the depth of walls. A 0.6 T_{vis} window transmits $0.6 \cdot 0.8^2 = 0.384$ percent of light to account for the lack of geometric specificity in EnergyPlus models. Finally, to address the third issue of coplanar surfaces, in the MRT view factor calculation models: all floors are translated upwards by 0.5 mm, all ceilings are translated downwards by 0.5 mm, and all walls are translated 0.5 mm opposite of the surface normal direction. By slightly moving the surfaces in this way, there is no ambiguity between whether a specific spatial location has a view to the front or back of any surface, which will have different temperatures.

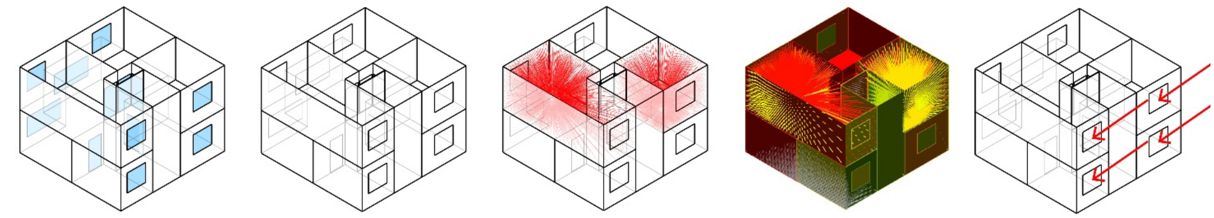
Sensor grids over which to calculate MRT, thermal comfort, and daylighting metrics are automatically generated 0.85 m above each floor plane in the thermal model at a user-settable uniform distance; however, custom grids can also be defined. Sensors are also associated with the thermal zone (or room) name they are contained within to be associated with data useful in calculating thermal comfort such as relative humidity and dry bulb air temperature.

Performance Simulation Engines

Annual daylighting simulations are calculated using the Daysim (Reinhart and Walkenhorst 2001) engine, which employs a daylight coefficient method calculating the contributions of 145 portions of the diffuse sky, 3 areas of ground reflectance, and approximately 65 direct solar positions. Hourly illuminance is predicted based on the Perez sky model paired with climatic datasets. Active shading systems such as blinds or electrochromic glazing are not accounted for in the calculations; therefore, the outputs are meant to be interpreted based on the potential for useful daylight and excessive light exposure as per contemporary standards and metrics such as Annual Sunlight Exposure (IESNA 2012) and Useful Daylight Illuminances (Mardaljevic, et al. 2012). To ensure adequate distribution of light, Radiance/Daysim simulation parameters are set as follows: ab=7, ad=2048, ar=2048, as=512, aa=0.1, lw=0.0001.

EnergyPlus simulations are run with hourly output utilizing the same climate data, and are forced to include the following outputs necessary for MRT and thermal comfort analysis in addition to those requested by the simulator: `Surface Inside Face Temperature`, `Zone Air Temperature`, `Zone Air Relative Humidity`, and `Zone Air Humidity Ratio`. If an airflow network (AFN) (Walton 1989) is used to calculate natural ventilation, the following outputs are also included such that volumetric flows throughout openings and thermal zones can be accounted for: `AFN Zone Infiltration Volume`, `AFN Zone Mixing Volume`, `AFN Linkage Node 1 to Node 2 Volume Flow Rate`, and `AFN Linkage Node 2 to Node 1 Volume Flow Rate`.

In this manuscript, all performance simulations for illustrative purposes utilize the Singaporean IWEC weather file and the conceptual model diagrammed in Figure 3. This model is based on the design of a retrofitted house by Richard Hyde in 1998 located in Brisbane, Australia (Hyde 2000) translated into a high-rise design. The design is built in EnergyPlus using uninsulated concrete floors, ceilings and walls as per typical Singaporean constructions. Windows are single pane, 3 mm glass with a solar control coating applied (SHGC=0.288; Tvis=0.65). Adiabatic adjacency



(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 2: Diagram of the calculation steps involved in spatializing radiant temperature results for TCA calculation across a sensor grid.

properties are applied to ceilings, floors and shared walls. Schedules and internal loads are based on the Building America House Simulation Protocols (Hendron and Engebrecht 2010). Free-running variants of the design with mechanical conditioning systems use an AFN with windows open when outdoor temperatures are below 28.5 C. Air-conditioned variants of the design maintain a sealed building envelope and are conditioned to 26 C when a space is occupied.

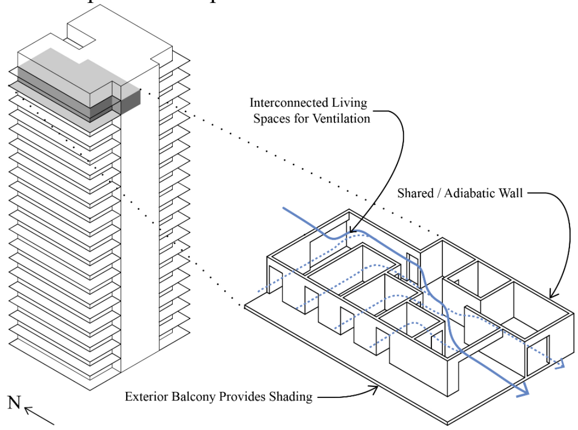


Figure 3: Conceptual model of the building used for data display examples in this manuscript.

Spatialization of Radiant and Comfort Information

Spatialization of thermal comfort results is valuable as it can be directly related to other intuitive spatial measures such as annual daylighting to better intuit building performance. To achieve this, mean radiant temperature (MRT) in the authors' proposed framework is calculated relative to surrounding surface temperatures before being adjusted for direct solar heat gains for each sensor grid in the analysis. The steps involved in this process are documented visually in Figure 2C–E. As described previously, thermal geometry and material properties are read in from an IDF file (2A), coincident wall surfaces are clipped by the windows, and fronts and backs are slightly offset to avoid view collisions—resulting in a Radiance format model (Ward 1994) (2B). Next, view factors are calculated between each sensor point in the grid and all surrounding building surfaces using a set of 2562 rays distributed in an equal solid angle manner (2C). This is achieved using the Radiance `rtrace` command with the `-oM` option to report the material name of the surface at each ray's first intersection for every sensor point. Finally, hourly inside surface temperature results from the EnergyPlus simulation are paired with the view factor calculations to derive hourly MRT (2D), and direct solar calculations are used to derive a solar adjusted mean radiant temperature at each hour attenuated by the solar heat gain coefficient and angle of transmission through the glazing (2E). The calculation of hourly solar adjusted MRT takes the form in Equation 1.

$$MRT = \sqrt[4]{\left(0.25 \cdot 0.7 \cdot \mathrm{E} \cdot \frac{1}{\sigma}\right) + \sum_{i=1}^{n_{VF}} \left(VF_i \cdot \mathrm{T}_{\mathrm{srf,i}}\right)^4} \qquad (1)$$

where E is hourly direct irradiation arriving at a sensor (W/m^2); σ is the Stefan–Boltzmann constant ($5.670367 \times 10^{-8}\ W/m^2K^4$); VF is the view factor (percent) from a sensor location to an individual surface, and T_{srf} is the hourly surface temperature (deg. K). 0.25 is a seated projection factor and 0.7 is a typical solar absorption factor for human skin. It should be noted that for sensors not receiving direct solar irradiation (E = 0), the MRT will simply be a function of the surrounding surface temperatures. Once MRT is spatially determined in this manner, it can be paired with associated thermal zone temperature and humidity levels to predict thermal comfort measures such as PMV, PPD, SET, and the ASHRAE 55 standards. The authors utilize a translation of the UC Berkeley CBE comfort tool calculations (Hoyt, et al. 2013) for this purpose.

Annual-Spatial Data Structures and Data Display

Any annual data set of 8,760 hours is interpreted as a conceptual 'zone,' which is derived from the thermal modelling term relating performance measures with a spatial component—typically an air volume; however, the authors do not limit the zone concept to this spatial unit. Zones can be a single point in space, a vector, a surface, or an air volume (an actual thermal zone). Annual performance data is required, because it facilitates a holistic understanding of performance across a complete weather cycle. For example, point zones can contain thermal comfort or climate-based daylighting information; vector zones can contain visual comfort information; surface zones can contain information about heat gains, losses, temperatures and volumetric air flows; and volumetric zones can contain air psychrometric properties, energy use information or any EnergyPlus zone-level output. Disparate simulation results from thermal, ventilation and daylight performance are organized within a single framework using the zone concept.

Once organized in the zonal geometric and annual data framework, results can be navigated and displayed in a variety of ways. Outputs can be quantified for display using several methods to assess temporal data:

- Average—the mean value during a specified time interval.
- Frequency—the percentage of time a value with a certain range is achieved.
- Sum—the total of values over a specified time interval.

An example of these display methods is shown in Figure 4 using an annual thermal model for a free-running, natural ventilated version of the building described previously. Figure 4A displays the annual average of mean radiant temperature for all 8760 hours in the year, and 4B displays the frequency of operative temperatures below 28.5 C. Finally, 4C illustrates the sum of zone-level solar hear gains normalized per floor area.

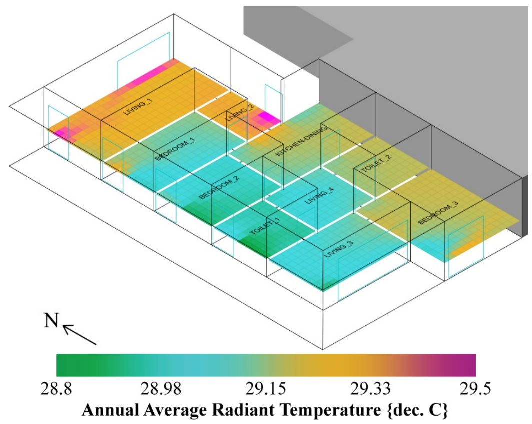
Because 'zone' data sets are comprehensive annually, outputs can be calculated and visualized across multiple time scales and schedules. It is therefore possible to switch between different seasonal, hourly, monthly, time-of-day, and annual outputs to enhance understanding of the design's performance. In contrast to Figure 4, Figure 5 illustrates thermal performance across a single, sunny day by displaying room-level normalized solar heat gains (solid color of the floor) and spatialized operative temperature calculations (colored dots) on an hourly basis. Starting at 8:00 until 17:00, direct solar gains can be seen to locally increase operative temperature in sunlit areas. During these times, the northern `LIVING_1` and `LIVING_2` thermal zones are negatively impacted by excessive solar gains.

Likewise, the benefits of external shading and the moderate glazed areas of `BEDROOM_1`, `BEDROOM_2`, and `TOILET_1` are visible. These spaces cool down most quickly in the evening (from 18:00 to 21:00 in Figure 5), and begin to heat up slightly as occupants utilize the space for sleeping. Relatedly, generally lower operative temperatures can be seen (4B) in these spaces throughout the year, and higher average radiant temperatures can be seen near unshaded windows than near more shaded windows (4A). While these outputs are not comprehensive and are mainly intended to illustrate different forms of temporal and spatial data communication, they show the potential for communication methods to enable better understanding of the performance of a design.

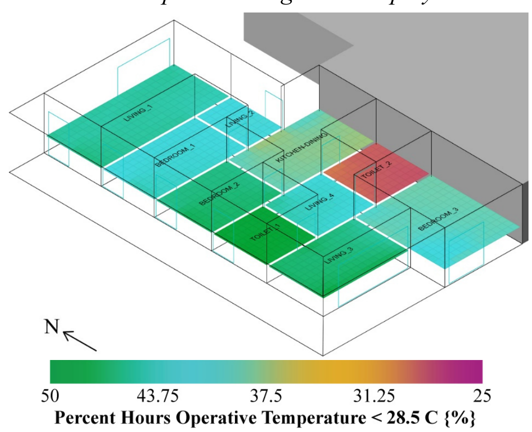
Suggested Performance Metrics

Passive, Free-Running Designs

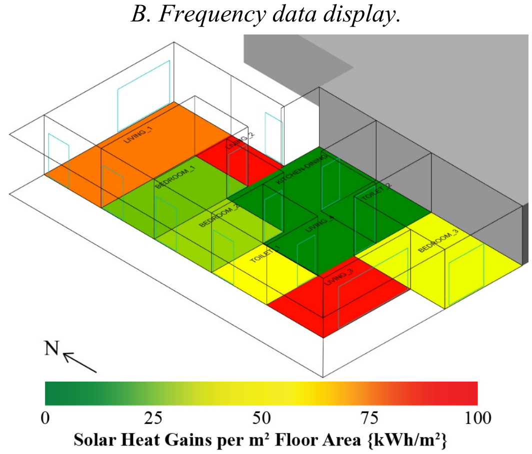
In passive architectural design concepts, three issues are typically under consideration: (1) daylighting, (2) natural ventilation and (3) thermal comfort. Appropriate display of performance metrics within the challenge of a passive design should account for these three considerations across space and time as well as for when they are within a beneficial range or exceed established values.



A. Temporal average data display.



B. Frequency data display.



C. Sum data display.

Figure 4: Depictions of three types of temporal and spatial thermal model output displays.

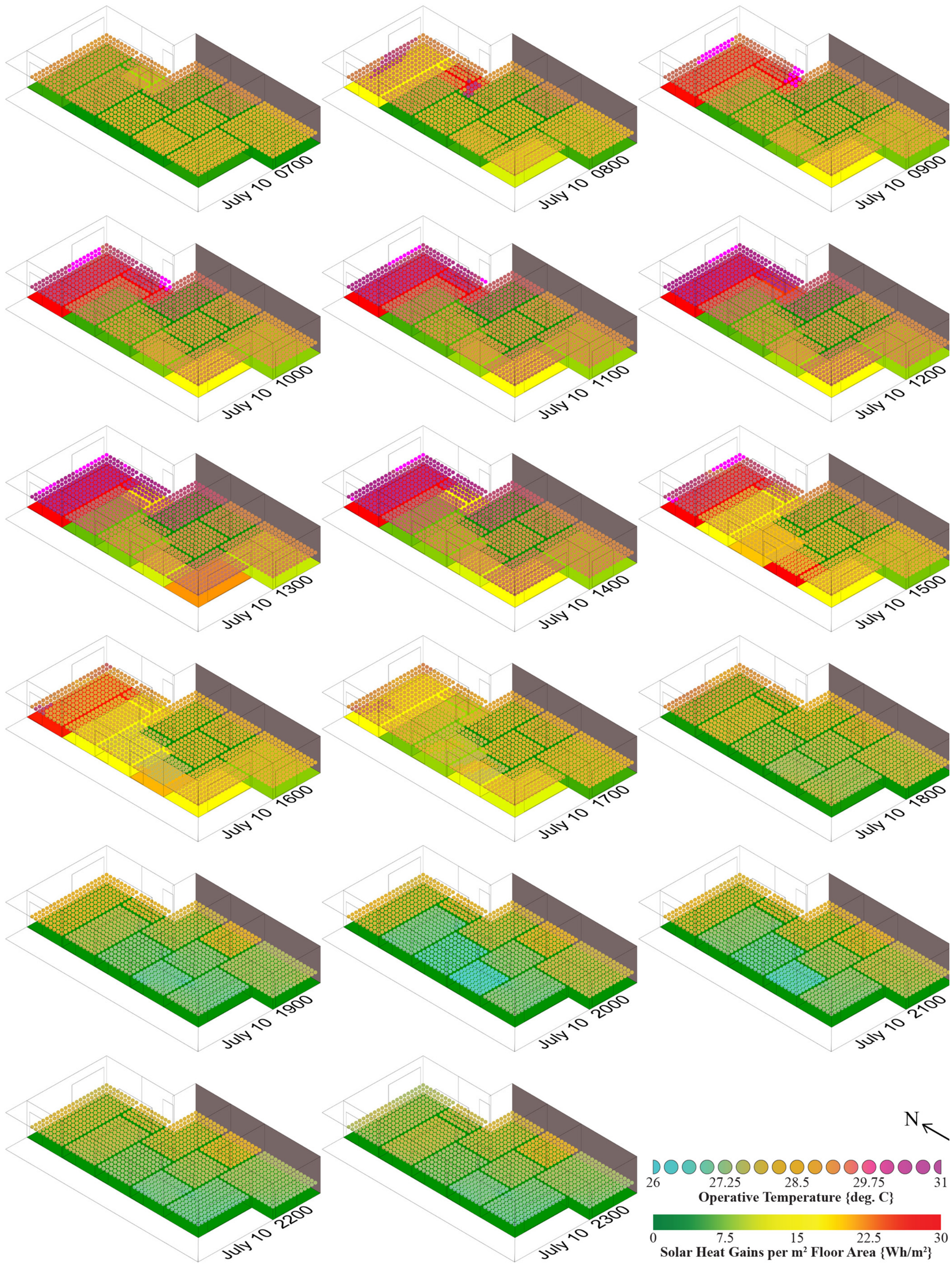


Figure 5: Hourly data display of predicted operative temperature and solar heat gains from 7AM until 11PM on 10 July.

Daylighting results should be visualized as the co-display of two metrics to account for beneficial lighting as well as overlighting. The authors suggest to use $UDIa_{300\ lx–3000\ lx}$ and $UDIe_{3000\ lx}$. $UDIa_{300\ lx–3000\ lx}$ is selected as it approximately matches a lighting threshold that relates to human perception of what is daylit (Reinhart, Rakha and Weissman 2014) but also discounts excessive daylight. $UDIa_{300\ lx–3000\ lx}$ can be 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. $UDIe_{3000\ lx}$ on the other hand identifies overlit areas that indicate increased potential for glare and visual discomfort (Mardaljevic, et al. 2012). Areas with a $UDIe_{3000\ lx}$ value greater than 15% of occupied hours are colored pink to indicate undesirable visual conditions and potential for excessive solar heat gains.

Ventilation information on an annual, hourly basis can be 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. An AFN is chosen because it is computationally limiting at this time to generate enough CFD results in order to populate an annual spatial zone as described in this manuscript. Ventilation results therefore are only spatially localized at the thermal zone and surface (opening) level. At the thermal zone level this can be 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 can be displayed as a surface output.

Mackey's (2015) concept of TCA is selected to display thermal comfort information, because it presents thermal comfort in the same terms and using the same climate data as climate-based daylighting metrics such as UDI. TCA represents the percentage of hours in a year where thermal comfort is achieved based on a specified comfort model. The authors recommend to calculate and display TCA (Mackey 2015) using the ASHRAE standard 55 adaptive thermal comfort model 90% acceptance threshold (DeDear, et al. 1998). Areas comfortable less than 35% of time in the year are colored pink to indicate unacceptable comfort, while values greater than or equal to 75% are considered good. This value scale has been derived for the Singaporean climate; however, such values may be tailored based on other climates' potential for passive thermal comfort.

Figure 6 illustrates a concept for an at-a-glance dashboard combining these three, passive metrics. Several performance issues and successes become immediately clear to a theoretical designer working with this building design. The northern living spaces (#1 & #2) receive a large amount of overlighting relative to their floor area, visible from the pink coloration on the daylight display. The ventilation concept of a connected core works well, receiving annual average ACH rates of 50 or above; however, the side bedrooms and bathrooms do not achieve as much ventilation from the schema and could perhaps benefit from greater connectivity to the main living spaces. The dining room and kitchen is therefore extremely well ventilated while having little direct connection to the outdoors and daylight. A moderately ventilated room at the building periphery without large relative areas of overlighting performs the best across this design, achieving TCA between 60 % and 70 %.

Active, Mechanically-Conditioned Designs

For mechanically-conditioned designs, design investigations focus on energy reduction rather than completely passive strategies; therefore, the authors suggest that natural ventilation and thermal comfort are not as critical when ventilation is handled mechanically and when active systems ensure thermal comfort. Annual EUI values suddenly become the most important results to assess the success of an active design. The display of thermal gains from external factors is also sensible, from: windows (as in Figure 4C), infiltration, conduction, etc. Interior loads due to lighting, equipment and occupancy also identify locations that are successful versus those that contribute to a higher overall energy utilization. These outputs are plotted in Figure 7 for an actively conditioned version of the design model.

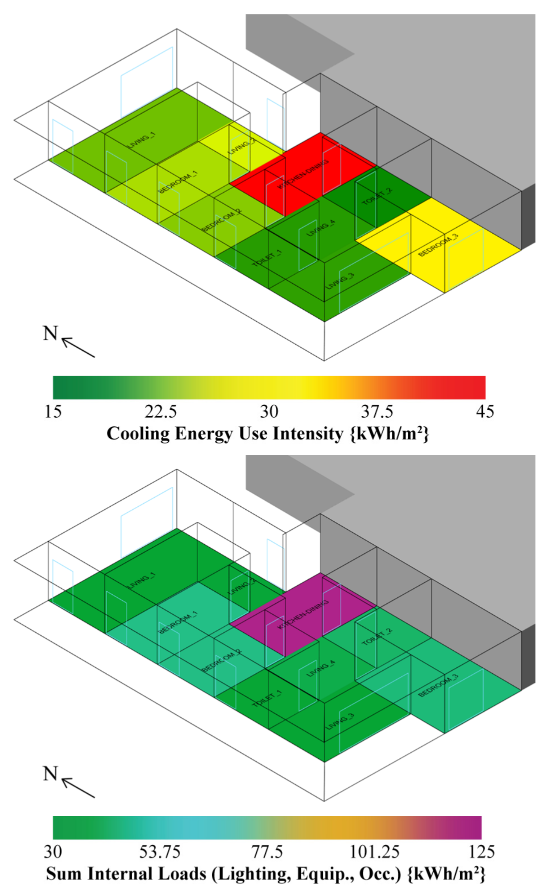


Figure 7: Mechanically conditioned metric outputs

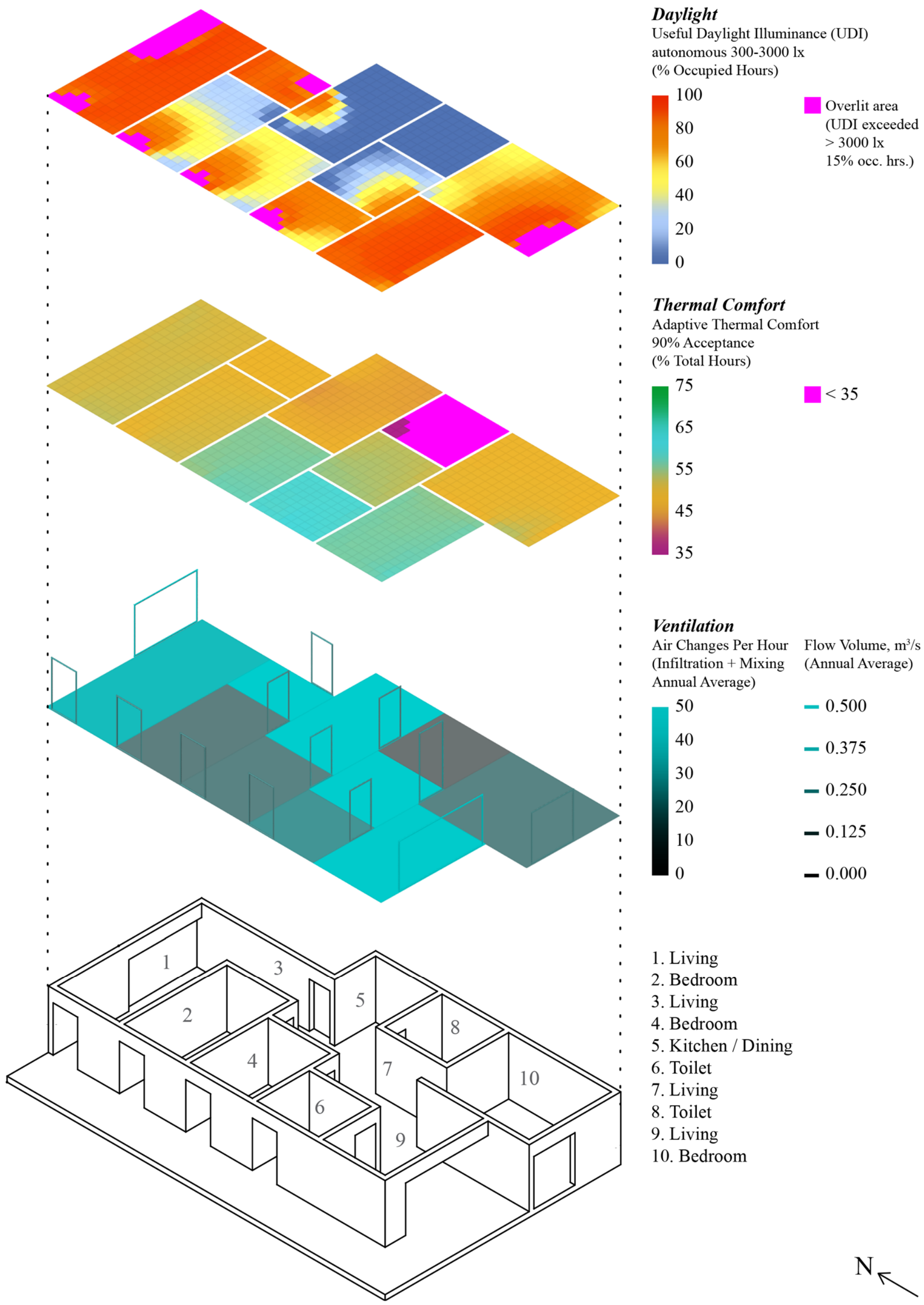


Figure 6: Proposed passive dashboard view illustrating spatial ventilation, thermal comfort, and daylighting results based on annual thermal, MRT and daylight performance simulations.

The display of daylighting and natural ventilation information is still worthwhile for actively conditioned buildings, especially if they are conditioned using a mixed-mode system that relies on passive strategies some of the time.

Discussion

The preceding sections describe a methodology for organizing and displaying disparate sources of BPS data to form spatial displays of building performance outputs and drive design understanding from an architectural point of view. The results are based on annual simulation data, are spatially discrete, and can be displayed and interpreted through a variety of temporal and statistical methods through the utilization of the spatial 'zone' data structure. A series of simple visualizations to describe the total performance of a passive architectural design strategies (Figure 6) was presented in addition to suggestions for data display of buildings with active conditioning systems. This section discusses some of the impacts and limitations of this methodology.

Relevance and Release of Tool

As covered in the introduction and review of communication methods sections, spatial data communication is important to enable intuitive design understanding. The methods outlined in this paper are implemented into a Grasshopper / Rhinoceros 3D plugin which takes as an input a single IDF file. Therefore, the goal is to create a large amount of actionable environmental data while minimizing the need for specialist modelling expertise. Referencing Figure 1, the simulation model can be created in any GUI which supports EnergyPlus such as DesignBuilder, DIVA-for-Rhino, Honeybee, OpenStudio, or Simergy. The model processing and generation of spatial data steps in Figure 1 are made possible through standalone Python programs which are independent of any paid software. Only the visualization and display framework reported herein is tied to a specific commercial software package—McNeel's Grasshopper environment for Rhinoceros 3D. An attempt has been made at creating a standardized results format which may be in the future readable by other display frameworks such as web-based tools or other building performance simulation GUI's.

The tool is based upon the Mr. Comfy plugin and will be released simultaneously with the publication of this paper. Users will be able to use spatially mapped thermal outputs, thermal comfort, daylight and ventilation to better comprehend, communicate and respond to a design's performance.

As with any method, time and effort required are important to consider when assessing impact potential. To generate the spatially specific thermal comfort and daylight results depicted in this paper, the simulation time was approximately 11 seconds per sensor using a single-core of a 2.4 GHz processor. This equated to a simulation time of approximately 3 and 1/2 hours for the display shown in Figure 6. For rapid design iterations, the density of sensors can be reduced, significantly lowering the time required. Effort in preparing the simulations and visualizations is often a larger concern than calculation time, as it takes direct human effort to prepare multiple simulation models rather than computer effort. Because the tool presented herein generates data from a single energy modelling input, the intent is to minimize time spent building separate models. In addition, all the building performance outputs displayed in this paper were completely generated using the tool, sans-editing with the exception of the axonometric building graphic at the bottom of Figure 6, the addition of North arrows and scale bars, and the CFD results displayed in Figure 8.

Limitations

One serious limitation of the tool is that AFN's in EnergyPlus do not actually allow for the extrapolation of spatially localized air velocity within spaces, only bulk volumetric flow through an air volume. CFD calculations would allow a deeper level of understanding of the ventilation performance of a space; however, as mentioned earlier, this is computationally infeasible, because a significant number of individual CFD calculations would be needed in order to fill the 'zone' data structure with 8760 hours of data. While recognizing this limitation, the authors did test a typical wind situation using CFD for the test building, which is depicted in Figure 8 below. It is compared against the annual average ACH data shown earlier. This is not a direct comparison because the result is annualized data (ACH) versus point-in-time data (m/s); however, it seems clear that ventilation trends do match between the two calculations. The authors look forward to a time where annualized CFD calculations are easily possible.

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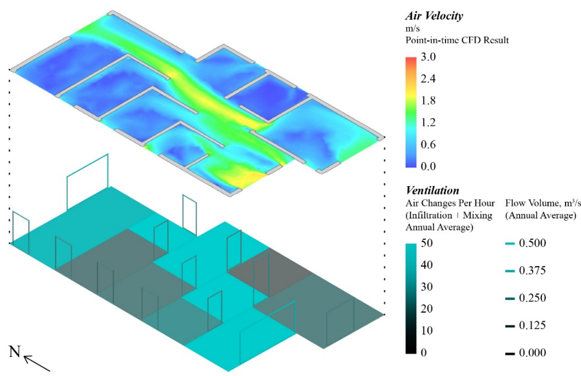

Figure 8: Comparison Between a Single CFD Result and Annual AFN Ventilation Simulation

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