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MAPPING COMFORT: AN ANALYSIS METHOD FOR UNDERSTANDING DIVERSITY IN THE THERMAL ENVIRNOMENT

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ABSTRACT

This paper describes the development and uses of a new software program called cMap that calculates and visualizes thermal comfort parameters throughout a space and over time.

While some existing tools provide comfort calculations either over space or throughout time, cMap provides both calculations, providing a more complete picture of our thermal environment. Since the program works as a companion to EnergyPlus, a cMap analysis can be performed quickly, fitting into existing analysis workflows.

Such a tool can be used to predict areas and periods of thermal discomfort, provide additional support for the use of energy-efficiency measures, and promote the use of thermal diversity in the built environment.

INTRODUCTION

Thermal comfort is partly a function of space. This is reflected both in our thermal experience and in our comfort standards. Consider, for example, the feeling of standing close to a cold window on a winter's day compared to standing further away from the window. That feeling is captured in our comfort standards through mean radiant temperature (MRT) which is a variable common to both the Fanger comfort model and the adaptive comfort model (ASHRAE 55-2010).

Architects also think and design spatially. Recognizing this, many building performance analysis tools provide visualization of results within a 3D modeling context. While this has been particularly true of daylight analysis tools (Jackubiec and Reinhart 2011; Mardaljevic 2004), the spatial visualization of thermal comfort parameters has been less common, despite the fact that it is spatially determined. Such spatial visualization could help idenitfy potential areas of thermal discomfort during the design process, among other uses.

This paper discusses the development and potential uses of a new software program called cMap. The goal of the program is to calculate and map thermal comfort parameters throughout a space and over time. The program is built to work with EnergyPlus in order to fit easily into existing analysis workflows.

There are currently a handful of simulation tools that are specifically geared towards the analysis of comfort in professional practice. These include the ASHRAE Thermal Comfort Tool (Fountain and Huizenga 1997), the UC Berkeley Advanced Human Thermal Comfort Model (AHTCM) (Huizenga et. al. 2001), EnergyPlus (U.S. Department of Energy 2012), and Arup's ROOM (White and Holmes 2009). Of these tools, only the ASHRAE Thermal Comfort Tool and EnergyPlus are publicly available; the other tools are currently limited in availability or proprietary.

These tools can be usefully characterized according to their scale of focus and their output over space and time. A tool's scale of focus could be on the human body or a thermal zone. A tool's spatial output (S-OUT) data could be for multiple points in space (MP), or a single point in space (SP). A tool's temporal output (T-OUT) data could be for a single point in time (SP), or over a range of times throughout the year (MP). Table 1 characterizes the tools discussed above.

Table 1: Comfort Tool Classification

NAME	SCALE	S-OUT	T-OUT
ASHRAE Comfort Tool	Zone	SP	SP
UC Berkeley AHTCM	Body	MP	SP
EnergyPlus	Zone	SP	MP
ROOM	Zone	MP	SP

As shown in Table 1, none of these existing analysis tools maps comfort parameters over multiple points in both space and time.

While computational fluid dynamics (CFD) analysis was not specifically developed to analyze thermal comfort, it is being increasingly used for this purpose in professional practice. Negrao (Negrao et. al. 1999) and Haves (Haves et. al. 2003) both provide examples of this process.

In addition to these tools, several recent research projects explore thermal comfort simulation methods. A number of these projects focus on predicting comfort on various parts of the human body using a multi-segment model. These include van Treek (van Treek et. al. 2009), Yang (Yang et. al. 2007), and Rees (Rees et. al. 2008). Other projects focus on predicting and visualizing comfort throughout a space, which is also the focus of the current work. These include Herkel (Herkel et. al. 1999), Gan (Gan 1994; Gan 2001), and Goffin (Goffin and Schlueter 2012).

METHODOLOGY

The cMap software program encompasses the following processes:

- **Input:** EnergyPlus .IDF and .CSV
- **Step 1:** Create 3D analysis grid
- **Step 2:** Calculate view factors
- **Step 3:** Calculate MRTs
- **Step 4:** Calculate comfort indices
- **Output:** Interactive 2D visualization

As currently constructed, cMap acts as a companion to EnergyPlus. After an EnergyPlus simulation is performed, the user can run cMap to get spatially resolved thermal comfort calculations and visualization.

The primary input to the cMap software is an EnergyPlus input data file (.idf) and a standard output comma separated value file (.csv). The .idf file provides data on the room geometry; the .csv file provides hourly data on room surface temperatures, dry bulb temperatures, and other environmental parameters.

cMap then creates a set of grid points across the x, y, and z dimensions of the space. Steps 2, 3, and 4 listed above are then performed at each individual grid point.

Calculating view factors can be a complex process; view factors are a function of the surface area and posture of the human body, as well as the location of a human body within a space. Cannistraro (Cannistraro et. al. 1992) developed an algorithm for the determination of view factors based on curve fitting the view factor nomograms in Fanger (Fanger 1970). This algorithm has been used in other cases (Bessoudo et. al. 2010) and is used within cMap to determine view factors in order to reduce computation time.

The view factors are then used to calculate the MRT at each grid point for every hour of the year. MRT is calculated according to Equation 1.

$$T_{MRT} = T_1 F_{P-1} + T_2 F_{P-2} + \ldots + T_n F_{P-n} \qquad (1)$$

The program then calculates the following set of thermal comfort indices at each grid point for every hour of the year:

- Operative Temperature
- Predicted Mean Vote
- Predicted Percentage Dissatisfied
- ASHRAE Standard 55 Adaptive Model
- EN Standard 15251 Adaptive Model
- NPR-CR 7251 Adaptive Model

These last three are all variations on the adaptive comfort model, and they differ primarily in the calculation method for the outdoor temperature. Details on these can be found in Borgeson (Borgeson and Brager

2011), Nicol (Nicol and Humphreys 2010), and van der Linden (van der Linden et. al. 2006).

These indices are calculated at each grid point using the MRT for that grid point and the additional relevant variables from the EnergyPlus simulation. For example, the operative temperature – a function of the MRT and the dry bulb temperature – is calculated at a given grid point for a given hour using the MRT for that grid point and the zone-averaged dry bulb temperature calculated in EnergyPlus. This distinction is important. While cMap produces a spatial mapping of thermal comfort, the only variable in the present version of the code that is spatially determined is MRT. All of the other comfort variables – dry bulb temperature, activity level, etc. – are zone-averaged results from EnergyPlus.

This approximation works in many common scenarios and should be appropriate in any case in which zone air is relatively well-mixed. For cases with stratified ventilation systems (e.g., displacement) this approximation is not appropriate; future work is needed to address these scenarios. Please see the Discussion section for additional limitations.

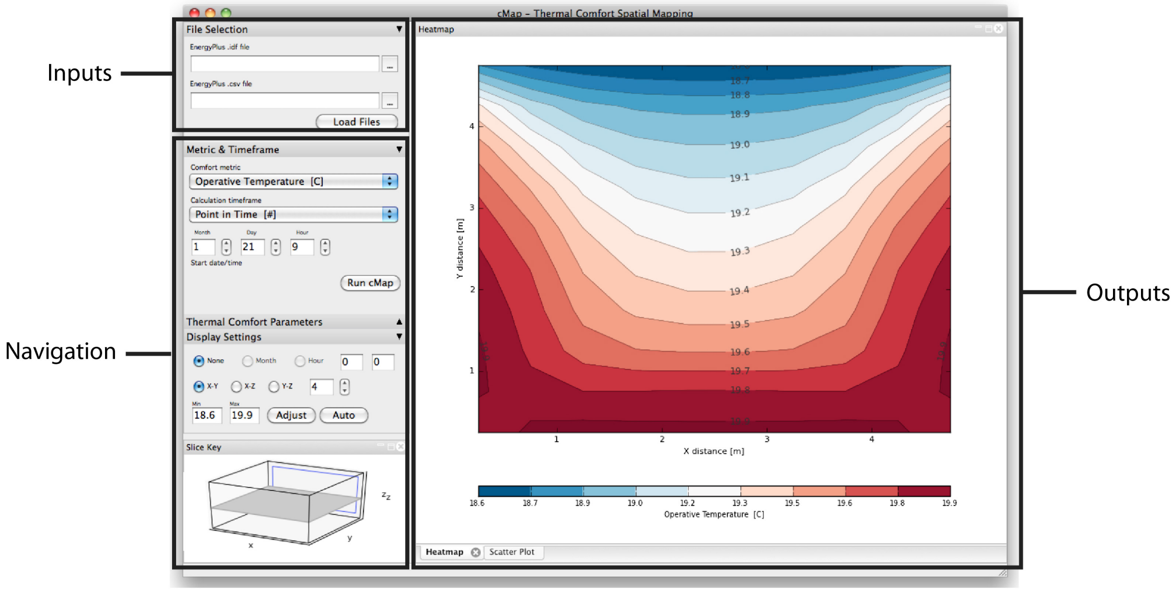
The results of the analysis are then displayed in a graphic user interface shown in Figure 1 below. There are two types of results shown. First, a 2D heatmap provides mapping of the comfort calculations throughout a space. The user is able to select which dimension to view (X-Y, Y-Z, X-Z) and is able to scroll sequentially through heatmap "slices" through the space. Second, a scatterplot plots the room-averaged comfort value at every hour of the year against the acceptable limits of the selected comfort index. The scatterplot is provided for convenience and indicates compliance with the selected standard.

DISCUSSION

Sample Simulation Output

The figures on the following pages provide an example of the cMap output. All of the cMap results shown are based on an EnergyPlus simulation using a single zone model with a large north-facing window, as shown in Figure 2. Model specifications are listed in Table 2. The simulation was performed using a weather file for Boston, MA.

Two simulation cases are shown here. Case 1 uses glazing with a code minimum U-value. Case 2 uses a very high performance window with a low U-value. The cases are evaluated at 9:00 am for each day in January, to simulate comfort for a building



Comfort metric: Operative Temperature [C]
Calculation timeframe: Point in Time [#]
Month: 1
Day: 21
Hour: 9
Start date/time
● None ○ Month ○ Hour 0 0
● X-Y ○ X-Z ○ Y-Z 4
Min: 18.6
Max: 19.9

Figure 1: cMap Graphic User Interface

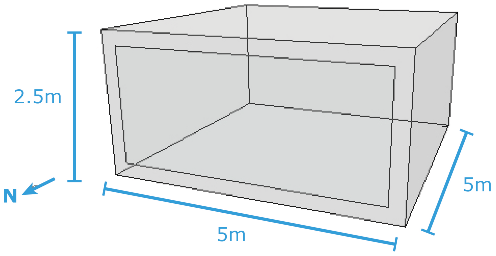


Figure 2: Model Geometry

Table 2: Model Specifications

PARAMETER	**VALUE**	**UNIT**
Walls	2.00	m^2-K/W
Roof	3.51	m^2-K/W
Floor	adiabatic	-
Window – Code Min	3.12	W/m^2-K
Window – Improved	0.78	W/m^2K

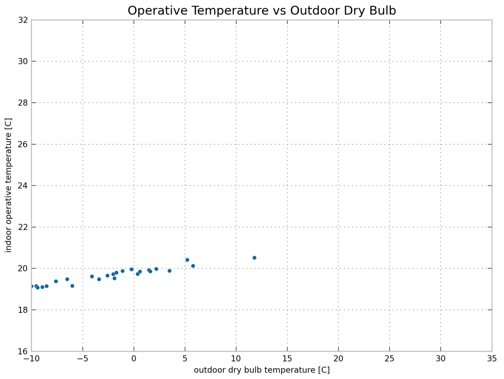


Figure 1: Case 1 Scatterplot

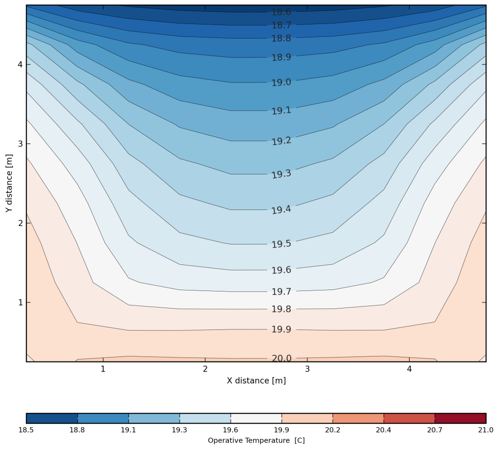


Figure 2: Case 1 Heatmap

occupant with a desk near the window.

Figures 3 and 4 provide results for Case 1. Figure 3 plots the room-averaged operative temperature (y-axis) against the outdoor dry bulb temperature (x-axis). Figure 4 shows a heatmap "slice" in the X-Y direction, taken 1.125 m off of the floor. Figures 5 and 6 provide similar results for Case 2

The results of the analysis show that the improved glazing increases the operative temperatures near the window. In Case 1, the operative temperatures near the window are around 18.5°C, which is below the comfort zone. The improved glazing also decreases the temperture drop across the space. In Case 1 the total temperature drop across the space is 1.4°C, while in Case 2 the total temperature drop is around 0.6°C.

While operative temperture can provide a useful starting point for thermal comfort

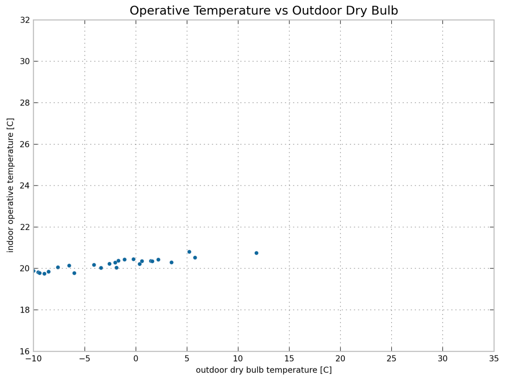


Figure 3: Case 2 Scatterplot

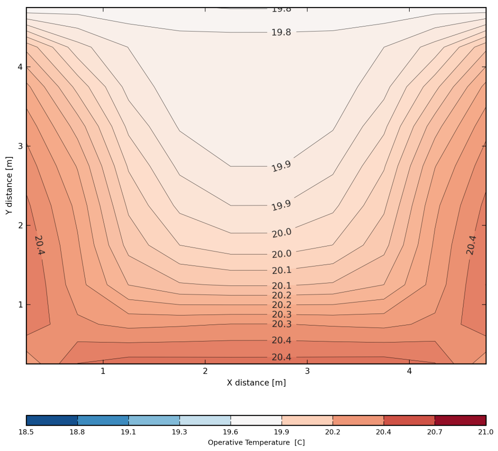


Figure 4: Case 2 Heatmap

analysis, the user can go on to select a different comfort index from the drop-down menu (e.g., PMV, PPD) to more directly compare these conditions to current thermal comfort standards

Capabilities and Limitations

cMap represents several improvements to existing thermal comfort analysis methods. Chiefly, cMap provides both spatial and temporal mapping of comfort parameters. cMap analysis can also be performed very quickly. In comparison to the ASHRAE Thermal Comfort Tool, parses thermal conditions from a thermal analysis program (EnergyPlus), rather than requiring the user to supply the thermal conditions of interest.

However, cMap currently has many limiations. It is only intended for use with a single zone EnergyPlus model, and does not account for spatial variation in variables other than MRT. Variations in air velocity, air temperature, and direct solar radiation within the space are not currently accounted for.

CONCLUSION

This paper discusses the development and uses of a new software program called cMap that calculates and visualizes thermal comfort parameters throughout a space and over time. There is a great deal of potential for the use of this and similar tools in professional practice. By providing spatially resolved information, such a tool can be used to predict areas and time periods of thermal discomfort. Such a tool could also help support the implementation of energy efficiency strategies in a project. While a strategy like triple-pane glazing may get value engineered out of a project based only on cost and expected energy reduction, providing additional information quantifying the thermal comfort benefits of the strategy could help it get implemented. This kind of information could be useful during the design stages of a new construction, or during an energy audit or retrofit period for an existing building.

Such a tool could also help promote an understanding of thermal diversity in the built environment. Most existing thermal analysis tools (with the exception of CFD) are built on the assumption that a thermal zone is uniform. But, as mentioned in the Introduction, we do not typically experience a space as being thermally uniform. Integrating analysis tools into professional practice that can visualize diversity in the thermal environment will help bridge the gap between our analysis methods and our actual experience in the built environment.

FUTURE WORK

Expansions to cMap's current methodology, as well as validation studies would help further this work.

cMap cannot currently account for spatial variation in variables other than MRT. Future versions of this tool could use approximations in order to account for spatial variation in air temperature due to ventilation schemes (e.g., displacement ventilation) or high local heat gains (e.g., a gallery space).

Although cMap uses a very different and much simplified method than CFD, a comparison to CFD results would provide a useful validation of the present work. cMap is intended to be a quick analysis tool built to work with existing energy analysis programs. Comparison to CFD analysis could quantify the tradeoffs between accuracy and speed of simulation time.

While it does not pertain solely to this work, a survey of researchers and practitioners regarding the use of and perceived need for thermal comfort analysis tools in professional practice would be helpful for the development of cMap and other similar tools.

As mentioned in the Introduction, daylight analysis tools have put particular emphasis in recent years on both spatial and temporal visualization of analysis results. One additional innovation in daylight analysis has been the development of "dynamic" or "climate-based" daylight metrics such as daylight autonomy, useful daylight illuminances (UDI) and annual light exposure (Reinhart et. al. 2006). Literature in the lighting and daylighting field has advocated for these dynamic metrics over "static" metrics such as daylight factor. Borgeson and Brager have initiated analogous work in the thermal comfort field with the use of "exceedance metrics" based on the percentage of occupied hours that fall outside of the desired comfort index range (Borgeson and Brager 2011). Such metrics could be easily incorporated into cMap to provide an annual aggregate evaluation of comfort conditions.

NOMENCLATURE

T_{MRT} = mean radiant temperature, ^{o}C
T_n = temperature of surface n, ^{o}C
$F_{P\text{-}n}$ = view factor between a person and surface n

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REFERENCES

ASHRAE. 2010. Standard 55-2010 Thermal Environmental Conditions for Human Occupancy. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Bessoudo, M., Tzempelikos, A., Athienitis, A. and Zmeureanu, R. 2010. Indoor Thermal Environmental Conditions near Glazed Facades with Shading Devices – Part I: Experiments and Building Thermal Model. Building and Environment 45: 2505-2516.

Borgeson, S. and Brager, G. 2011. Comfort Standards and Variations in Exceedance for Mixed-Mode Buildings. Building Research and Information 32(2): 118-33

Cannistraro, G., Franzitta, G., and Giaconia, C. 1992. Alogorithms for the Calculation of the View Factors between Human Body and Rectangular Surfaces in Parallelpiped Environments. Energy and Buildings 27(1): 83-96.

Fanger, P. 1970. Thermal Comfort: Analysis and Application in Environmental Engineering. New York: McGraw-Hill.

Fountain, M., and Huizenga, C. 1997. A Thermal Sensation Prediction Software Tool for use by the Profession. ASHRAE Transactions 103:130-36.

Gan, G. 1994. Numerical Method for a Full Assessment of Indoor Thermal Comfort. Indoor Air 4: 154-168.

Gan, G. 2001. Analysis of Mean Radiant Temperature and Thermal Comfort. Building Serv. Eng. Res. Technol. 22(2): 95-101.

Goffin, P., and Schlueter, A. 2012. Visualization Framework of Thermal Comfort for Architects. Proceedings of the Symposium on Simulation for Architecture and Urban Design (SimAUD) 2012.

Haves, P., de Graca, G., and Linden, P. 2003. Use of Simulation in the Design of a Large Naturally Ventilated Commercial Office Building. Proceedings of Building Simulation 2003.

Herkel, S., Schoffel, F., and Dionisio, J. 1999. Interactive Three-Dimensional Visualization of Thermal Comfort. Proceedings of Building Simulation 1999.

Huizenga, C., Hui Z. and Arens, E. 2001. A Model of Human Physiology and Comfort for Assessing Complex Thermal Enviroments. Building and Environment 36: 691-99.

Jackubiec, J.A., and Reinhart, C.F. 2011. DIVA 2.0: Integrating Daylight and Thermal Simulations Using Rhinoceros 3D, DAYSIM and EnergyPlus. Proceedings of Building Simulation 2011.

Mardaljevic, J. 2004. Spatio-temporal Dynamics of Solar Shading for a Parametrically Defined Roof System. Energy and Buildings 36: 815-823.

Negrao, C., Carvalho, C., and Melo, C. 1999. Numerical Analysis of Human Thermal Comfort Inside Occupied Spaces. Proceedings of Building Simulation 1999.

Nicol, F., and Humphreys, M. 2010. Derivation of the Adaptive Equations for Thermal Comfort in Free-Running Buildings in European Standard EN15251. Building and Environment 45(1): 11-17.

Rees, S., Lomas, K., and Fiala, D. 2008. Predicting Local Thermal Discomfort

Adjacent to Glazing. ASHRAE Transactions 114: 131-141.

Reinhart, C.F., Mardaljevic, J., and Rodgers, Z. Dynamic Daylight Performance Metrics for Sustainable Building Design. Leukos 3(1): 7-31.

U.S. Department of Energy. 2012. EnergyPlus version 7.0.0. www.energyplus.gov.

van der Linden, A., Boerstra, A., Raue, A., Kurvers, A., and de Dear, R. 2006. Adaptive Temperature Limits: A new Guideline in the Netherlands – a new Approach for the Assessment of Building Performance with Respect to Indoor Climate. Energy and Buildings 38: 8-17.

van Treeck, C., Frisch, J., Egger, M. and Rank, E. 2009. Model-adaptive Analysis of Indoor Thermal Comfort. Proceedings of Building Simulation 2009.

White, A. and Holmes, M. 2009. Advanced Simulation Applications using ROOM. Proceedings of Building Simulation 2009.

Yang, T., Cropper, P., Cook, M., Yousaf, R., and Fiala, D. 2007. A New Simulation System to Predict Human-Environment Thermal Interactions in Naturally Ventilated Buildings. Proceedings of Building Simulation 2007.