DEVELOPMENT OF A DESIGN TOOL TO SIMULATE THE THERMAL PERFORMANCE OF DIRECT GAIN PASSIVE SOLAR SYSTEMS USING TMY3 DATA

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ABSTRACT

This article introduces a new simulation tool to evaluate and optimize the thermal performance of Direct Gain (DG) passive solar heating systems. *DG_Performance* is an interactive Microsoft Excel™ spreadsheet that allows users to modify relevant parameters that influence the thermal performance of a Direct Gain building, namely the area and type of glazing used; the area, thickness, and type of thermal mass; and the level of insulation of building envelope components. This design tool provides users with hourly indoor air and thermal mass surface temperatures during any given month selected by the user. In its present form, the program doesn't incorporate any back-up mechanical heating options. This tool is ideal for parametric design optimization of Direct Gain systems.

To illustrate the level of accuracy of *DG_Performance*, this article also presents a summary of the calibration study done using experimentally acquired data measured in an 11.9 m^2 test-room located in Muncie, Indiana.

1. DIRECT GAIN SIMULATION TOOLS

During the 1970s and 1980s passive solar heating was extensively researched in the United States. As a result, a series of simplified design guidelines were developed by various authors (Balcomb et. al, 1984; Niles and Haggard, 1980; Mazria et. al, 1977). Due to the limited capabilities of computers and the difficulty to access them in the 1980s, most passive solar heating guidelines were intentionally developed using a "worksheet" format that could be completed by using a standard calculator and a series of reference tables and/or sensitivity curves. While these guidelines were highly useful in advancing the principles of passive solar design and effectively contributed to the construction of over 180,000 passive solar homes in the United States (Balcomb, 2006), their format has become obsolete given the many technological advances already available to architects and designers in the 21st Century.

1.1 Whole-building Simulation Tools

Several computer programs were developed in the 1980s to simulate passive solar heating systems (e.g., PASOLE or CALPAS). However, due to rapid changes in computer programming languages and operative systems, but perhaps and more importantly, due to a significant reduction in funding for passive solar research, these programs never reached the level of maturity required for their adoption and extensive use by architects and designers.

In the 1990s, the increased capabilities of computers and the emergence of computer aided design, along with the development of advanced fenestration and building systems, produced an interest in simulation programs that take into consideration all the potential uses of energy in buildings. As a result, very robust "whole-building" simulation programs such as TRNSYS or DOE-2 gained popularity among researchers and practitioners involved in the design of large and/or innovative buildings.

While whole-building simulation programs have developed a more user-friendly interface in recent years, they have also become more complex and of very limited use for the kind of parametric exploration that architects and designers need to conduct during the early stages of the design process. When looking at architecture education, Peters (2012) argues that most students who are interested in the design of sustainable buildings find it difficult to learn and/or use building simulation software. To that end, he suggests the development of easier-to-use simulation tools for the conceptual and schematic design phases (Peters, 2012).

Given the exploratory nature of the early phases of the design process, it seems logical to use a variety of simple simulation tools that could help architects and designers investigate and understand specific issues or components of a building.

1.2 Parametric Design Simulation Tools

While whole-building simulations are critical to improve a building's performance during the design development phase, parametric design tools can be used earlier in the process to guide the design of a building and select specific components.

Among the issues that should be investigated early on during the design of a building is the use of passive solar heating. To that end, Peters (2012) developed the *SolarShoeBox*, a visual modeling tool designed to simulate a simple rectangular building that is passively heated using Direct Gain and cooled by natural ventilation. This article focusses on an alternative to the *SolarShoeBox* by introducing a parametric design tool to simulate the thermal performance of Direct Gain systems using a Microsoft Excel™ interactive spreadsheet.

2. DG PERFORMANCE DESCRIPTION

DG_Performance is an interactive Microsoft Excel™ tool that allows users to modify relevant design parameters that influence the thermal performance of Direct Gain (DG) systems. *DG_Performance* is able to carry out hourly single-zone energy-balance simulations using TMY3 weather data. The program provides three different outputs to its users: the Solar Heating Fraction (SHF) calculated using Wray and Best (1987) generalized Solar Load Ratio correlations; the SHF calculated after the annual simulation of the building in question; and the hourly indoor air and thermal mass surface temperatures of the simulated building.

2.1 Using *DG Performance*

DG_Performance allows its users to investigate the effects and relationship among the parameters that influence the thermal performance of a passively heated building featuring Direct Gain, namely the area and type of glazing used; the area, thickness, and type of thermal mass; and the level of insulation of building envelope components. Because of its user-friendly interface (users only need basic familiarity with Microsoft Excel™), the program allows for multiple optimizations in a very short period of time, making *DG_Performance* a powerful design tool for the early stages of the design process.

DG_Performance uses three "tabs" within the spreadsheet to interact with its users. The first tab provides instructions to import TMY3 weather data (see Fig. 1). In the second tab the users enter the building information necessary to conduct the hourly simulation (see Fig. 2). In the second tab the users can modify: the areas and R-values of envelope components; the areas and type of fenestration used; and the amount, location, and thermal properties of the thermal storage featured within the building by using a series of dropdown menus and/or manual entries. Finally, the third tab presents the results of the simulation in the three formats previously described (see Fig. 3).

3. DG PERFORMANCE VALIDATION

DG_Performance was validated using experimental results from an 11.9 m^2 test-room operated with two different thermal storage configurations (Fernandez-Gonzalez, 2007). The test room, located in Muncie, Indiana, used a solar collector made of 6mm clear insulated glass (double glazing with 12.7 mm air space) with an aluminum frame featuring a thermal break (whole assembly U-value = 3.22 W/m^2 C°). The Solar Heat Gain Coefficient (SHGC) at the center of the glass at normal incidence was 0.70 (ASHRAE, 2001). The test room had a ratio of solar collector area (south-facing vertical fenestration) to floor area of 1:2.78.

The thermal storage mass in the first configuration (DG Configuration #1, see Fig. 4) was composed of 115 solid concrete blocks (20 cm by 40 cm and 10 cm thick) laid directly on the floor of the cell. The ratio of solar collector area to exposed thermal mass was 1:2.15. This ratio falls below the minimum of 1:3 recommended by Balcomb et al. (1984), which made the DG test-cell more susceptible to experience midday overheating during clear winter days.

The second thermal storage mass configuration (DG Configuration #2, see Fig. 5) included an additional 66 solid concrete blocks arranged as parapet walls on the east and west side of the test room, bringing the total number of concrete blocks to 181 units. The ratio of solar collector area to exposed thermal mass in the second configuration was 1:3.38. The second configuration also featured additional insulation mounted on the interior of the access door.

3.1 DG Configuration #1 Results

Experimentally measured air and mass surface temperatures were compared with the simulated values obtained by *DG_Performance* (see Fig. 4). The results of the calibration using the first configuration of the test room (ratio of solar collector area to floor area of 1:2.78) show good agreement between measured and simulated thermal mass surface temperatures, particularly during clear, sunny days.

Figure 1. Instructions to convert and insert TMY3 weather data into *DG_Performance*.

TMY3 Climate Data Summary

Instructions to Import Data from your TMY3 Weather File:

1. Click the link to the National Renewable Energy Laboratory (NREL) website provided below and select the city for which you want to obtain climate data

http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/by_state_and_city.html

2. Save the "**.csv**" file on your "**DG_Performance**" folder and then **open** it in Microsoft Excel™

3. Select the entire worksheet using the button on the upper left corner (between "Row 1" and "Column A")

4. Copy the selected worksheet and **paste** it on the "**TMY Data**" worksheet of the "**DG_Conversion.xls**" file

5. Make sure the data is pasted on the same location it had on the original ".csv" file **(the name of your city's weather station should be on cell B1)**

6. Go back to the "**Conversion**" worksheet of the "**DG_Conversion.xls**" file

Instructions to Export the Climate Data:

1. Select and **copy** the array: **[A27 : N9054]**

2. Open the file "**DG_Performance_v1.xls**"

3. Open the worksheet "**Climate Data**"

4. Select the destination cell **[A27]**

5. From the "**Edit**" menu **select** the "**Paste Special**" option

6. Select the "**Values and Number Formats**" option and then **select** "**OK**"

7. Save the changes to your TMY file

8. Close your TMY file and proceed ro work on "**DG_Performance_v1.xls**"

For your convenience these instructions are also available on the "Conversion" worksheet of the "DG_Conversion.xls" file

Hourly Climate Data

Date	Time	GHI	DNI	DHI	TotCld	Dry-bulb	Dew-point	Rhum	Pressure	Wdir	Wspd	Alb	Lprecip depth
(MM/DD/YYYY)	(HH:MM)	(W/m2)	(W/m2)	(W/m2)	(tenths)	(°C)	(°C)	(%)	(mbar)	(degrees)	(m/s)	(unitless)	(mm)
Insert on "A27"													
12/21/1979	1:00	0.00	0.00	0.00	9.00	12.20	-3.90	33.00	935.00	180.00	5.70	0.23	0.00
12/21/1979	2:00	0.00	0.00	0.00	9.00	12.80	-2.80	34.00	935.00	180.00	9.30	0.23	0.00
12/21/1979	3:00	0.00	0.00	0.00	10.00	12.80	-1.70	37.00	935.00	210.00	9.30	0.23	0.00
12/21/1979	4:00	0.00	0.00	0.00	10.00	12.20	-1.70	38.00	934.00	210.00	7.70	0.23	0.00
12/21/1979	5:00	0.00	0.00	0.00	10.00	10.60	1.70	54.00	933.00	190.00	8.80	0.23	0.00
12/21/1979	6:00	0.00	0.00	0.00	10.00	10.00	2.20	59.00	933.00	190.00	7.20	0.23	0.00
12/21/1979	7:00	0.00	0.00	0.00	10.00	9.40	2.80	63.00	934.00	200.00	6.70	0.23	0.00
12/21/1979	8:00	12.00	0.00	12.00	10.00	10.00	1.70	57.00	934.00	290.00	4.60	0.23	0.00

Figure 2. Instructions to insert building information data into *DG_Performance*.

Instructions to Complete the "Building Data" Worksheet:

1. Enter the required building information into the corresponding **yellow cell**s, or by selecting the appropriate values from the **drop-down menus** provided.

2. This worksheet requires all inputs to be in **S.I. Units**. For your convenience, appropriate conversion factors (I.P. to S.I. units) are provided for each input.

3. The insulation requirements of the **IECC 2009** (expressed as R-values) are provided as reference for your convenience on the U.S. map to the right of these instructions. To convert R-values to U-values use the following expression: **U-value = 1 / ΣR**

NOTE: The insulation requirementes presented in the U.S. map are on I.P. units --please be sure to convert these values to S.I. units.

General Information:

Building Floor Area	128.0	m²	$(1\ ft^2 = 0.0929\ m^2)$
Average Height of the Building Floor Area *(Min. = 2.3 m)*	2.30	m	$(1\ ft = 0.3048\ m)$
Infiltration Air Changes Per Hour *(Min. = 0.35 ; Max. = 1.05)*	0.35	1 / h	--
Upper Thermostat Setting *(Recommended = 22.2 °C)*	22.2	°C	$[°F - 32]*0.5555 = °C$
Lower Thermostat Setting *(Recommended = 18.0 °C)*	18.0	°C	$[°F - 32]*0.5555 = °C$

Floor:

Type of Floor	1. Slab on grade		
Perimeter of Floor	48.0	m	$(1\ ft^2 = 0.0929\ m^2)$
F_2 Coefficient of Floor Assembly (Slab on Grade Floor)	1.00	W / m C°	$(1\ Btu/h\ ft\ F° = 1.729\ W/m\ C°)$
U-value of Floor Assembly (Floor Above Crawling Space or Basement)	0.30	W / m² C°	$(1\ Btu/h\ ft^2\ F° = 5.678\ W/m^2\ C°)$
Area of Floor *Without Exposed Thermal Mass*	64.0	m²	$(1\ ft^2 = 0.0929\ m^2)$
Area of Floor *Covered By Exposed Thermal Mass*	64.0	m²	$(1\ ft^2 = 0.0929\ m^2)$

Thermal Properties of Exposed Thermal Mass (Floor):

Thickness of Floor Thermal Mass	0.152	m	$(1" = 0.0254\ m)$

Roof:

U-value of Roof Assembly

Ceiling Area *Without Exposed Thermal Mass*

Ceiling Area *With Exposed Thermal Mass*

Thermal Properties of Exposed Thermal Mass

Thickness of Ceiling Thermal Mass

Thermal Conductivity of Ceiling Thermal Mass

Density of Ceiling Thermal Mass

Specific Heat of Ceiling Thermal Mass

R-49 Ceilings
U-0.35 Windows
R-20 Walls
R-30 Floors
R-15 Foundations

All of Alaska in Zone 7 except for the following Boroughs in Zone 8:

Bethel, Dellingham, Fairbanks N. Star, Nome, North Slope, Northwest Arctic, Southeast Fairbanks, Wade Hampton, Yukon–Koyukuk

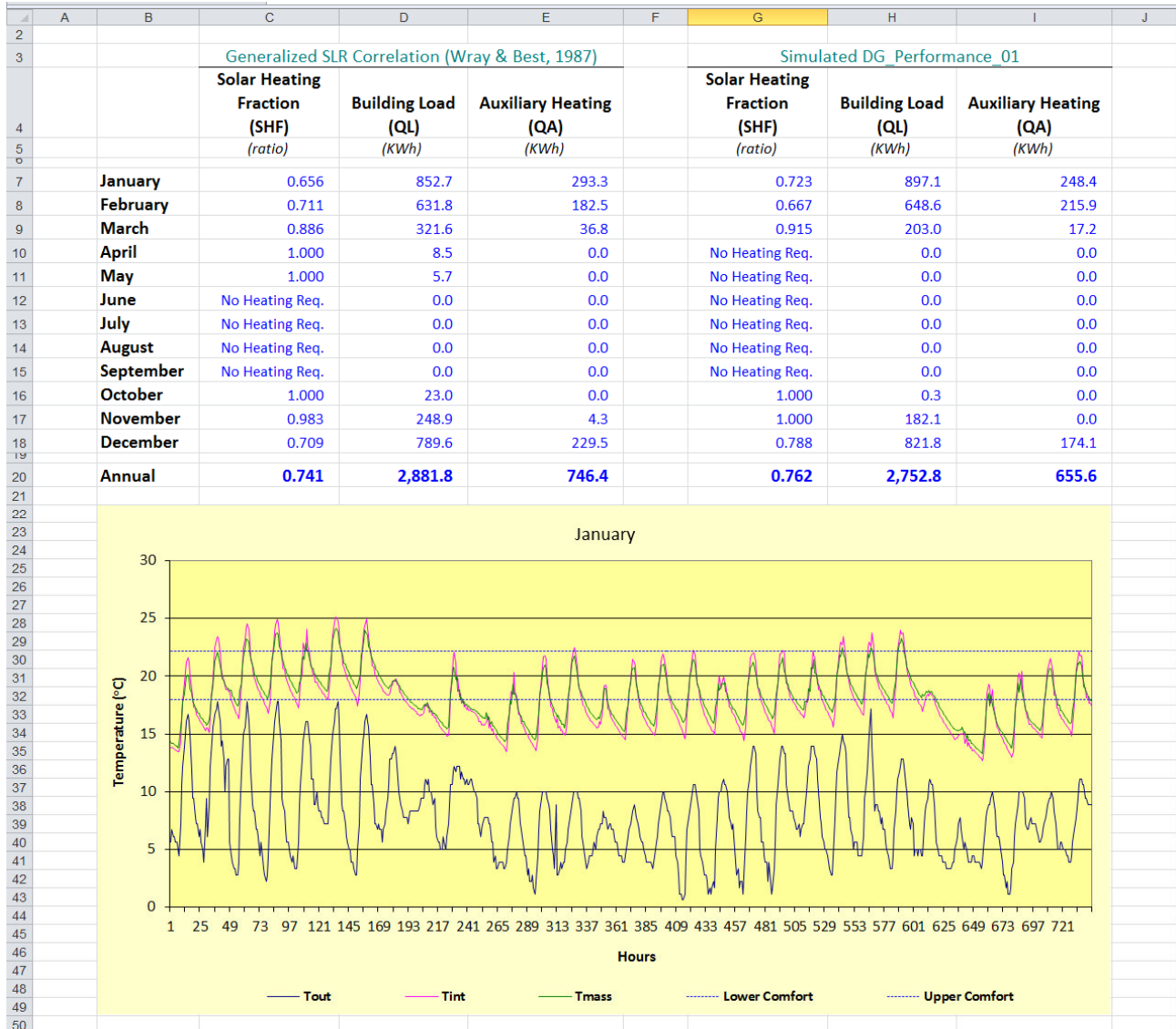|		Generalized SLR Correlation (Wray & Best, 1987)				Simulated DG_Performance_01		
		Solar Heating Fraction (SHF)	Building Load (QL)	Auxiliary Heating (QA)		Solar Heating Fraction (SHF)	Building Load (QL)	Auxiliary Heating (QA)
		(ratio)	(KWh)	(KWh)		(ratio)	(KWh)	(KWh)
January		0.656	852.7	293.3		0.723	897.1	248.4
February		0.711	631.8	182.5		0.667	648.6	215.9
March		0.886	321.6	36.8		0.915	203.0	17.2
April		1.000	8.5	0.0		No Heating Req.	0.0	0.0
May		1.000	5.7	0.0		No Heating Req.	0.0	0.0
June		No Heating Req.	0.0	0.0		No Heating Req.	0.0	0.0
July		No Heating Req.	0.0	0.0		No Heating Req.	0.0	0.0
August		No Heating Req.	0.0	0.0		No Heating Req.	0.0	0.0
September		No Heating Req.	0.0	0.0		No Heating Req.	0.0	0.0
October		1.000	23.0	0.0		1.000	0.3	0.0
November		0.983	248.9	4.3		1.000	182.1	0.0
December		0.709	789.6	229.5		0.788	821.8	174.1
Annual		0.741	2,881.8	746.4		0.762	2,752.8	655.6

Figure 3. Example of results produced by *DG_Performance*.

Measured and simulated air temperatures display good agreement in the evenings and early mornings, however *DG_Performance* under-predicted daytime maximum temperatures. A possible explanation for this discrepancy may be that solar radiation hit the air temperature sensor inside the test room in the middle of the day.

3.2 DG Configuration #2 Results

DG_Performance was also validated against experimentally measured air temperatures recorded during the period featuring the second configuration of the test room (ratio of solar collector area to floor area of 1:3.38). The simulated values obtained with *DG_Performance* show very good agreement with the experimentally measured air temperatures, though the program still slightly under-predicts the daily maximum air temperatures during clear sunny days (see Fig. 5).

Given the fact that the under-prediction of daytime maximum temperatures is significantly more pronounced in the initial configuration of the test room (which had less thermal mass storage), the under-prediction of maximum indoor air temperatures might be a consequence of the way in which *DG_Performance* simulates the "absorption" of solar gains by the room air.

The accuracy of *DG_Performance* is considered to be acceptable for the intended uses of this program (i.e. preliminary architectural design).
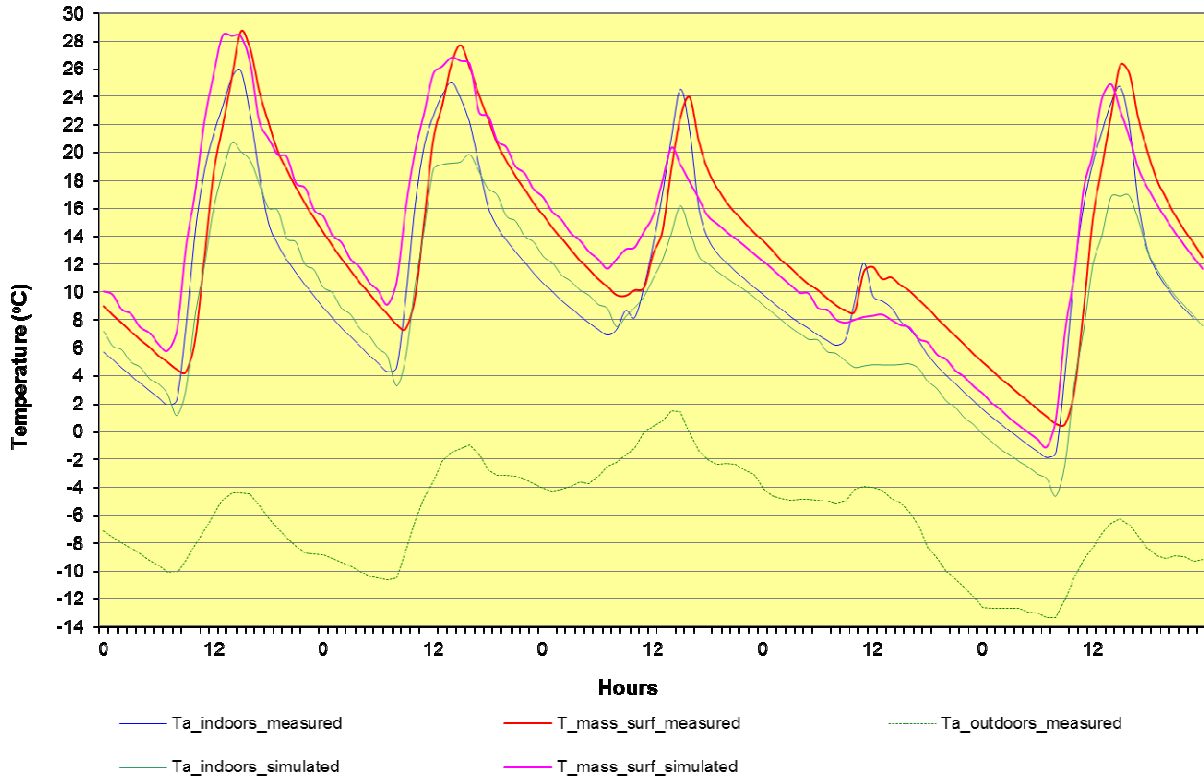
Figure 4. *DG_Performance* **validation using DG Configuration #1 and measured data from January 10-14, 2003**
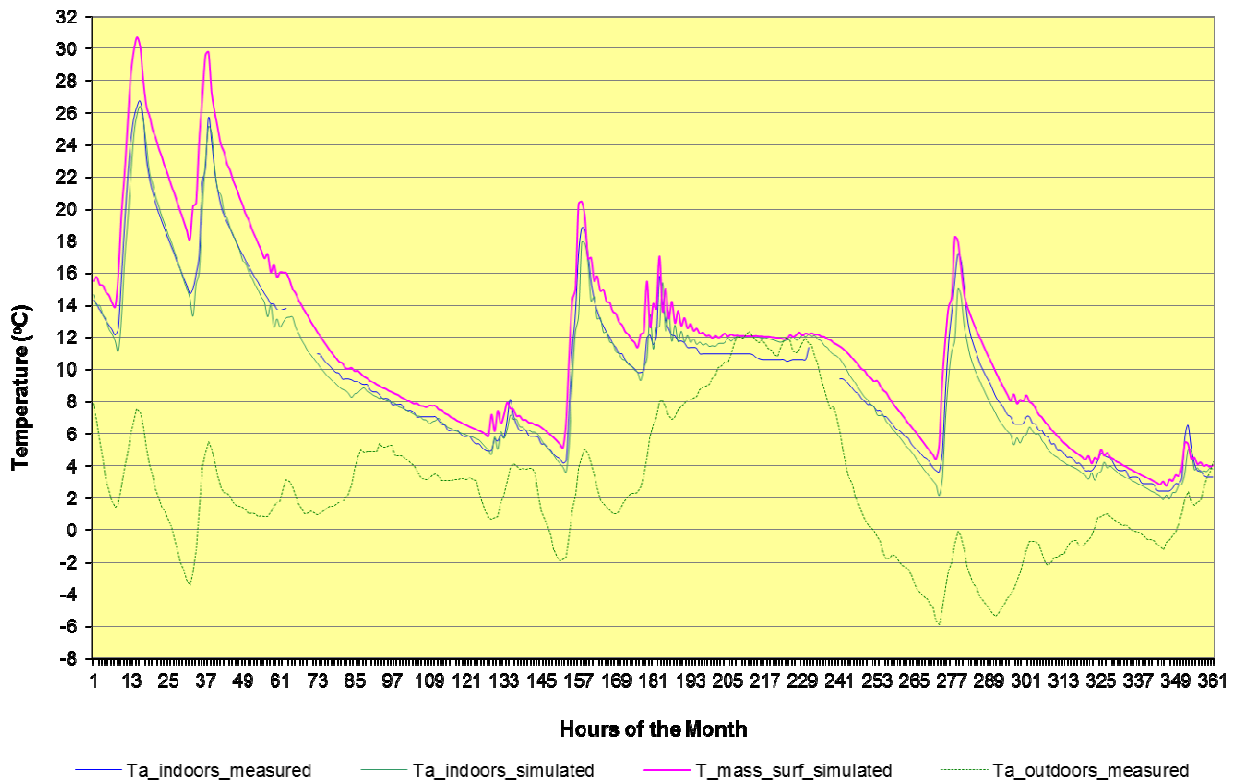

Figure 5. *DG_Performance* **validation using DG Configuration #2 and measured data from December of 2003**

4. CONCLUSIONS

DG_Performance allows students, architects, and designers to consider the implications of including passive solar heating early on during the design process. The program attempts to make energy analysis a part of the schematic design phase and not something that happens once a building's design has been finalized.

The validation of the program suggests that it is reasonably accurate for use during the initial steps of the design process, where it can have great impact over the formal decisions that will ultimately determine the building's actual energy consumption.

5. REFERENCES

(1) ASHRAE. 2001. *Handbook of Fundamentals*. Atlanta: American Society of Heating Refrigeration and Air-Conditioning Engineers, Inc.

(2) Balcomb, J.D. 2006. *Passive Solar Comeback Ahead*. Solar Today. September/October 2006, pp. 24-29

(3) Balcomb, J.D. (Editor). 1992. *Passive Solar Buildings (Solar Heat Technologies)*. Cambridge: MIT Press

(4) Balcomb, J.D., R. Jones, R. McFarland and W. Wray. 1984. *Passive Solar Heating Analysis*. Atlanta: American Society of Heating Refrigeration and Air-Conditioning Engineers, Inc.

(5) Fernandez-Gonzalez, A. 2007. *Analysis of the thermal performance and comfort conditions produced by five different passive solar heating strategies in the United States Midwest.* Solar Energy, Volume 81, Issue 5, pp. 581-593

(6) Mazria, E., Baker, M.S. and Wessling, F.C. 1977. *An analytical model for passive solar heated buildings.* Proceedings of the American Section of ISES: 1.2, 11-10 to 11-14. Cape Canaveral: International Solar Energy Society

(7) Niles, P.W.B. and Haggard, K.L. 1980. *Passive Solar Handbook for California*. Sacramento: California Energy Commission

(8) Peters, T.N., *SolarShoe Box*. http://solarshoebox.com/ Last accessed February 2013

(9) Peters, T.N. 2012. *Teaching Passive Solar Design to Beginning Design Students.* Proceedings of the 2012 World Renewable Energy Forum. Boulder: American Solar Energy Society

(10) Wray, W.O. and Best E.D. 1987. *Thermal Storage in Direct Gain Buildings: The Effective Heat Capacity and a Generalized Solar Load Ratio Correlation.* Passive Solar Journal, Volume 4, Issue 1, pp. 41-61