

# Linking Detailed Solar Collection Data to a Parametric Model for Accurate Performance Analysis Throughout the Design Process

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**Abstract:** The paper summarizes the efforts of an elective design studio in which a parametric model was linked to detailed energy output data in order to provide accurate feedback about building performance throughout the entire process of design. Photovoltaic collection data was downloaded from the National Renewable Energy Laboratories (NREL) and linked directly to alternative configurations of designs produced in SolidWorks. Microsoft Excel provided the direct link between the model and data where students were able to augment the SolidWorks Excel output to include calculations that referenced the NREL data. The program from the 2009 Solar Decathlon competition served as the program for the investigation and provided a constraint-rich environment for developing parametric models. The class also utilized morphological analysis to identify 13 different forms to develop and analyze. The resulting parametric models and analysis provided a focused introduction to design methods, parametric modeling and solar energy design.

Keywords: Parametric model, PVWATTS calculator, SolidWorks Excel output, building performance

## **1 INTRODUCTION**

In the current climate of sustainability and alternative energy, managing the conflict between a building form that simultaneously maximizes solar energy collection, minimizes energy loss, and provides a delightful architectural experience is a considerable challenge. Balancing criteria that operate at cross purposes, such as a desire to have walls made of glass vs the energy liability represented by large expanses of glazing, is challenging for the most experienced designers. Developing these skills is even more challenging for the beginning architecture student. The rapidly changing scene of technology in architectural practice further adds to the complexity of architectural education as the profession moves from a 2-D based project delivery paradigm to a 3-D Building Information Modeling paradigm. The integration of parametric modeling in the early education of an architecture student offers a method for students to develop understanding of the fundamental issues that drive their designs as well developing a deep

understanding of technical information, such as solar energy collection, and its impact on design. Consequently, the motivation for this effort was to develop a pedagogical instrument that simultaneously introduces students to concepts of parametric modeling and exposes students to the challenges and details of integrating photovoltaic solar energy collection in building design. The goal of this effort was two fold - to provide more accurate than rules-of-thumb feedback about performance throughout design development and to model the drivers (or design graph structure) of the form in order to defer the final decisions about the specifics of each design (Aish and Woodbury 2005). To explore this strategy a parametric model was developed that linked the parameters of an emerging design to external data for solar collection, cost and heat loss. The resulting models and variations allowed for very quick analysis of several forms comparing the energy collection, energy loss and spatial characteristics of each one. Through interaction with parametrically driven models, students quickly learned the cause and effect of de-

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cisions and could rapidly explore alternative strategies and evaluate performance.

The paper continues with three additional sections to explain the work of an elective studio and the development of the parametric instrument. Section 2 of this paper describes the context of the project and overall methods used to produce the parametric models. Section 3 concentrates on the actual parametric models describing the linking of the parameters to performance data. Section 4 provides a conclusion and future explorations.

### 2 DESCRIPTION OF THE SOLAR HOUSE STUDIO

#### 2.1 Program

The rules of the 2009 Solar Decathlon competition were used as the program for the development of the parametric design models. "The U.S. Department of Energy Solar Decathlon challenges 20 collegiate teams to design, build, and operate solar-powered houses that are cost-effective, energy-efficient, and attractive" (http://solardecthalon.gov). The competition goal is to produce a house that:

- 1. Is affordable, attractive, and easy to live in;
- 2. Maintains comfortable and healthy indoor environmental conditions;
- 3. Supplies energy to household appliances for cooking, cleaning, and entertainment;

- 4. Provides adequate hot water; and
- 5. Produces as much or more energy than it consumes.

Additionally, the competition includes several hard constraints that needed to be met and these constraints served to further limit the scope of the studio so that design efforts could be accelerated. The three constraints that had the most impact on the designs and the parametric modeling exercise were:

- 1. A square footage limitation of 650 square feet minimum and 1000 square feet maximum;
- 2. A  $50' \times 80'$  site with an 18' high maximum solar envelope; and
- 3. A 13' 6'' tall maximum transportable height.

Since none of the 13 students in the studio had any previous parametric modeling experience, the tightly constrained and well-documented rules and outcomes of previous Solar Decathlon competitions provided a straightforward path to learning both the software and the rule-based strategies necessary for developing parametric models.

#### 2.2 Analysis and Data Immersion

The publication "Precedents in Zero-Energy Design: Architecture and Passive Design in the 2007 Solar Decathlon" provided rapid insight into the primary parameters that would drive the modeling process in the studio (Zaretsky 2009). Reviewing the concepts and forms of the 2007 competition houses revealed that



Figure 1. Concept diagrams from the precedents in zero-energy design book



Click on **Calculate** if default values are acceptable, or after selecting your system specifications. Click on **Help** for information about system specifications. To use a DC to AC derate factor other than the default, click on **Derate Factor Help** for information.



(Type comments here to appear on printout; maximum 1 row of 80 characters.)

SITE LOCATION: Results Station Identification CELL ID: 0247375 City: Dayton Solar AC Energy Ohio STATE : Radiation Month Energy (kWh) Value State: Ohio (\$) (kWh/m<sup>2</sup>/day LATITUDE . 39 071 Latitude 39.90° N 3.08 304 25.84 1 LONGITUDE : -84.584 Longitude 84.22° W 2 3 54 308 26.18 Elevation 306 m 4.08 32.81 3 386 PV SYSTEM SPECIFICATIONS: PV System Specifications 4 5.17 460 39.10 DC RATING (KW): 4.0 DC Rating: 4.0 kW 5 5.32 470 39.95 DC TO AC DERATE FACTOR: 0.77 DC to AC Derate Factor 0.770 6 5 54 458 38.93 AC Rating: 3.1 kW ARRAY TYPE: Fixed Tilt 7 5.44 462 39.27 Array Type: Fixed Tilt 8 5.68 488 41.48 FIXED TILT OR 1-AXIS TRACKING SYSTEM: 39.9 Array Tilt: 9 5.05 425 36.12 ARRAY TILT (DEGREES): 39.071 (Default = Latitude) Array Azimuth: 180.0 4.79 10 435 36.98 180.0 (Default = South) Energy Specifications ARRAY AZIMUTH (DEGREES): 11 2.88 262 22.27 Cost of Electricity 8.5 ¢/kWh 12 2.36 227 19.30 ENERGY DATA: Year 4.41 4685 398.23 COST OF ELECTRICITY (CENTS/KWH): 7,272 Output Hourly Performance Data Output Results as Text ABOUT THE HOURLY PERFORMANCE DAT. SAVING TEXT FROM A BROWSER Calculate HELP Reset Form RUN PVWATTS V.1 FOR ANOTHER US LOCATION OR AN INTERNATIONAL LOCATION RUN PVWATTS V.2 (US ONLY)

Figure 2. PVWATTS input and output screens for a 4kW array in Dayton, Ohio

 "PVWATTS: Hourly PV Performance Data"
 "Year

 "City:", "DAYTON"
 1988,

 "State:", "Ohio"
 1988,

 "Lat (deg N):", 39.90
 1988,

 "Long (deg W):", 84.22
 1988,

 "Elev (m):", 306
 1988,

 "Array Type:", "Fixed Tilt"
 1988,

 "Array Tilt (deg):", 39.9
 1988,

 "Array Azimuth (deg):", 180.0
 1988,

 "DC Rating (kW):", 4.0
 1988,

 "DC to AC Derate Factor:", 0.770
 1988,

 "AC Rating (kW):", 3.1
 1988,

"Year", "Month", "Day", "Hour", "AC Power (W) " 1988, 1, 1, 01:00, 0 1988, 1, 1, 02:00, 0 1988, 1, 1, 03:00, 0 1988, 1, 1, 04:00, 0 1988, 1, 1, 05:00, 0 1988, 1, 1, 06:00, 0 1988, 1, 1, 07:00, 0 1988, 1, 1, 08:00, 0 1988, 1, 1, 09:00, 163 1988, 1, 1, 10:00, 763 1988, 1, 1, 11:00, 1939 1988, 1, 1, 12:00, 2930

Figure 3. Hourly output of data for a particular azimuth and tilt

most designs incorporated transportability issues as major design strategies and presumably optimized the east-west axis for maximum exposure to light and collection potential. Figure 1 illustrates the overall forms forms and concepts of 10 of the 2007 Solar Decathlon houses with the longer east-west axis and limited widths to facilitate transportation to the National Mall in Washington DC. Further analysis of precedent also revealed a wide range of approaches to balance collection opportunities with architectural character.

To provide direct understanding of collection efficiency, the studio referenced the PVWATTS calculator available from the National Renewable Energy Laboratories (NREL) (http://rredc.nrel.gov/solar/calculators/PVWATTS/version2/).

The calculator produces tabular values of hourly so-

lar output collected for particular locations. The test site data for Dayton, Ohio was incorporated in the studio since this was the closest data collection site for the hypothetical site in the studio. The web-based software allows the user to enter the tilt and the azimuth of the array, then returns a table of expected annual energy collected per month based on averages collected over several years. Figure 2 illustrates the input and output screens of the PVWATTS calculator.

The calculator also provides a download of the hourly data collected over the years for that particular latitude, azimuth and tilt. Hourly data points for every 10 degrees of azimuth between 90 and 270 degrees and every 5 degrees of tilt from 0 to 90 degrees were downloaded into an Excel spreadsheet. These data were then directly linked to the parameters of emerging designs that affected collection. Figure 3 illustrates a small sample of the hourly output for one square foot of collection from the PVWATTS calculator.

The resulting spreadsheet yielded 1,830,840 data points with a watt output value associated for every hour of the day in a year. The size of this data table in Excel resulted in extremely slow behavior so some of the data points were culled to reduce the size of the table and improve performance. For example, all times after sunset and before dawn had 0 watts of output so it was justifiable to eliminate those data points.

#### 2.3 Process

While it is recognized that parametric modeling can be used to derive form, such as the Embryological House by Greg Lynn (http://embryologicalhouse.com/) with only 10 weeks in the academic term and the lack of student experience with parametric modeling, the parametric operations were focused on driving forms that have already been determined at a schematic level. Consequently, morphological analysis, developed by Fritz Zwicky, was applied to systematically produce various forms for exploration (Ritchey 2004). 13 of the most promising options were selected and each student was assigned one form strategy to model and develop. It was quickly determined that the most influential design variable was whether the photovoltaic collection was a fixed or tracking array. This produced two major branches of options with unique sub-design variables. Figure 4 illustrates the initial paths that were assigned to the students and a few of the form concepts.

Students continued to use the Zwicky method to explore their individual designs in order to arrive at a set of basic parametric rules to model and drive their final form based on direct feedback from the linked data. The remainder of the academic term then focused on the development of the parametric models and on using linked solar collection data to fine tune and optimize specific design choices for individual designs. As a final exercise, each of the thirteen schemes was compared in a summary evaluation to assess which combination of form and collection strategy provided the most efficient output of watts for the least cost and the least energy loss while providing the richest architectural character and interior qualities.

## 3 THE PARAMETRIC MODELS AND LINKS TO DATA

### 3.1 Establishing the Parametric Models

The basic behavior of the parametric model was developed using the constraints and objectives of the Solar Decathlon Competition rules within SolidWorks. SolidWorks was chosen as the modeling software environment for 4 practical reasons:



Figure 4. Morphological analysis for assigning overall form studies

- 1. The software was readily available in the college labs;
- 2. The college has faculty and staff with expertise using SolidWorks;
- 3. SolidWorks is easy to learn especially for students with no prior parametric experience; and
- 4. SolidWorks uses Excel providing a simple bridge between the model and data.

The constraint of square footage was used as the first parameter to model. While the Decathlon rules mandate that the overall footprint of the house be between 650 square feet and 1000 square feet, the square footage was artificially constrained to 800 for all schemes in order to normalize the comparisons at the end of the term. After a brief introduction to the foundations of constraint-based design (Gross 1996) and the use of a sketch to drive form Kolarevick (1994), students developed a plan geometry sketch to respond to the site constraints and square footage limits for the overall form adopted from the morphological analysis exercise. As experience with the concepts grew, more in-depth texts on parametric design strategies were introduced (Woodbury 2010). Figure 5 shows one example of a design sketch for a form where the plan follows the arc of the sun and two variations of form if the square footage is constrained.

Once the behavior of the constrained plan was established, attention shifted to modeling the parameters and behavior of the section. With both tracking and non-tracking solutions considered, the individual



Figure 5. Plan sketch using square footage constraint to explore alternatives



Figure 6. Section parameters for horizontal fins for one scheme and roof slope for another

models used the sun's angle to drive the design in different ways. For example, for a scheme with horizontal wall mounted photovoltaic collection fins, the parametric sketch driving the components in the section takes the summer solstice angle of the sun as the constraint to determine the spacing of the fins. If one considers larger fins, the spacing between them adjusts to avoid self-shading during the summer. For a building form that incorporates the collection area on a sloping roof surface, the roof angle is modeled as the variable with the height of the north wall constrained to the maximum 18 feet allowed by the competition rules. When combined with the 800 square feet constrained plan geometry, the resulting forms clearly illustrate the balance that must be struck between maximizing collection area at the expense of useable floor area. Figure 6illustrates the section sketch that drives the horizontal fin placement on the left and the roof angle and resulting form options on the right.

#### 3.2 Linking to Solar Collection Data

When the sketches driving the plan and section were complete, configurations within SolidWorks were defined so that evaluation could be quickly accomplished when the data links were made. The intent here is to provide immediate visual feedback about a design as well as accurate numerical performance information to aid in the early phases of decision-making (Danahy 1988). While tools like EcoTect already provide good analysis of emerging designs, the design is not parametrically linked to a sketch making accurate modeling of alternatives a bit cumbersome. By using the variables to drive design alternatives, dimensions can be extracted directly from the parametrically defined model to calculate areas of collection, the orientation of collection areas and areas of wall surface for any configuration under consideration.

The first attempts to link the large Excel spreadsheet with NREL data resulted in unacceptable delays in navigation. Neither Excel nor SolidWorks are well suited for working with extremely large file sizes. Consequently, the process was simplified to consider only performance at three times during the day, 10am, 1pm and 4pm, for four days of the year, December 21st, March 21st, June 21st and September 21st. Consequently, the resulting watt output reference tables were reduced to 1140 rows for each of the 4 dates. Following this, each student modified the calculation table according to the idiosyncrasies of their design. For instance, a scheme with multiple fixed facets for collection needed a row in the spread sheet for every facet as each facet has a different azimuth and tilt for a particular time and date. The values for azimuth, tilt and square footage were extracted from the Solid-Works configuration table where students constructed the formulae to capture the geometry as the sun moved or as their designs changed. Figure 7 shows one de-



Figure 7. Student configuration table with columns for area, azimuth, tilt

$\diamond$	A	B	C	D	E	F	G	H	$\diamond$	A	В	C	D	E	F
1		3/21							1	Month	Day	Hour	Azimuth	Tilt	Watt
2		Hour	Azimuth	Tilt	Watt	Area	Watts Produced	Hourly Totals	2		3 21	10:00	0	C	0
3		10:00	120	90	257	120	493.44		3		3 21	10:00	90	(	218
5		10:00	120	90	257	242	995.104		4		3 21	10:00	100	(	218
7		10:00	180	90	160	120	307.2		5		3 21	10:00	110	(	218
9		10.00	120	90	257	120	493.44		6		3 21	10:00	120	C	218
11		10.00	120	20	247	794	3035 648	5324 832	7		3 21	10:00	130	C	218
12		10.00	100	20	272	100	3033.070	JJ27.032	8		3 21	10:00	140	(	218
15		13:00	120	90	354	120	6/9.68		9		3 21	10:00	150	(	218
15		13:00	120	90	354	242	1370.688		10		3 21	10:00	160	C	218
17		13:00	180	90	562	120	1079.04		11		3 21	10:00	170	C	218
19		13:00	120	90	354	120	679.68		12		3 21	10:00	180	(	218
21		13:00	180	20	720	784	9031.68	12840.768	13		3 21	10:00	190	C	218
23		16:00	120	90	100	120	192		14		3 21	10:00	200	(	218
25		16:00	120	90	100	242	387.2		15	_	3 21	10:00	210	C	218
27		16:00	120	90	303	120	581.76		16		3 21	10:00	220	(	218
20		16:00	120	90	100	120	192		17	_	3 21	10:00	230	(	218
21		16.00	120	20	100	704	5202.02	(746.00	18		3 21	10:00	240	(	218
22		16.00	100	20	430	704	J373.72	0/40.00	19		3 21	10:00	250	C	218
32					202 2222		1//0.022		20		3 21	10:00	260	(	218
33		monthiy	Average		303.3333		1660.832		21		3 21	10:00	270	(	218
35	Annual watt collection potential per hour					hour	69565.024	watts/hour	22		3 21	13:00	0	(	0
							2.40	K 11	23		3 21	13:00	90	0	599
37			average coll	ection time	per day $= 5$	hours	348	KwHours	24		3 21	13:00	100	(	599

Figure 8. Excel calculation table of design output and calculation with reference table link



Figure 9. Watt output for Horizontal vs Vertical fin deployment

sign configuration table in which columns were added to contain the calculations that converted dimensions from SolidWorks into areas, azimuth and tilt.

Once the students augmented their SolidWorks configuration tables to capture their design variables, the overall calculation sheet and NREL data tables were added to their Excel files as additional sheets. The watt data downloaded from the NREL PVWATTS calculator were for a one square foot of collection area making it a simple task in Excel to multiply the total area of collector for that time, azimuth and tilt by the watt output for a collector with those variables. In some cases, the design spreadsheet had as many as 20 rows of calculated values for each time based on the complexity of the shape and position of the various collection areas. The values for area, azimuth and tilt were passed to the calculation table where the potential watt output was determined using the DGET formula in Excel:

=DGET('March 21'!\$C1:\$F1141, "Watt", 'Energy In'!B2:D3)

Figure 8 illustrates the simplified calculation table for the March 21st collection times and the first few rows of the March 21st data that were appended to the configuration tables in SolidWorks.

For comparison purposes, the totals for each time on each day were summed to produce a relative potential watt output that could be compared to the other schemes on an hourly, monthly and yearly basis. Three specific configurations for 10am, 1pm and 4pm were developed for each form exploration to capture sample performance over the course of the day. This strategy simplified the process and offered strong feedback to aid in decision-making. For example, for the scheme with photovoltaics mounted on fins, conventional knowledge suggested deploying the fins in the vertical orientation on the East and West walls and horizontally on the south wall. However when analyzed using the linked NREL data it was clear that the vertical orientation offered no advantage over horizontal deployment for the east and west walls. This allowed for the consistent deployment of horizontal fins all the way around the structure with no compromise in energy production. Figure 9 illustrates the comparison produced by the two configurations and Figure 10 shows the final scheme rendered with all horizontal fins.



Figure 10. Final design illustrating horizontal louvered photovoltaic collection

Another example of how the form studies were affected by using these data occurred with the fixed wedge schemes. Once again, rule-of-thumb wisdom would set the angle of the wedge equal to the latitude, e.g., 39.77 degrees off the horizon for Dayton Ohio. However, from very early tests of the geometry, students discovered that over the course of an entire year, a 26 degree angle produced the most watts for a fixed, south facing array. This discovery could then become a constraint in the parametric model instead of a variable if the main goal was to optimize annual production.

In addition to the watt output, each student used values drawn from the model to calculate heat loss. The extraction of area values from the configuration table were used to perform simple energy migration calculations using an assigned R-value for walls, floor and roof across the studio so one could compare the relative losses and gains while considering the architectural layout. This facilitated the exploration of many configurations so a reasonable tradeoff between watts in, watts out and functionality could be made. A similar strategy was used to crudely calculate overall construction cost based on the values drawn from the model as well. After settling on a single configuration that best balanced losses with production and cost all 13 schemes were compared to each other and subjectively evaluated. The purpose of a subjective evaluation was to help illustrate the reality that the most efficient scheme objectively may be uninspiring or even dysfunctional for the inhabitants. All 13 schemes shared the 800 square feet requirement, the same site, and the same data for cost, energy production and heat loss. This served to normalize the evaluation across all schemes. The subjective criteria included functionality, flexibility, ease of assembly, overall aesthetic appeal, the quality of light, views, privacy and spatial quality. All students in the class, as well as guest critics, evaluated the schemes against all criteria. The numerical scores were averaged into a single overall subjective score for each of the schemes. This "crowd sourcing" strategy neutralized any personal bias of the professor and provided a method to include collective personal taste and opinion into the evaluation.

The final results for subjective and objective analysis were tabulated and presented in a summary format to see which of the schemes performed the best in each of the evaluation categories. To no surprise, the schemes with tracking photovoltaic panels produced the most energy for the least cost since they optimized the deployment of the most expensive component. If the objective is to simply capture as much energy as one possibly can with no regard to cost, the scheme with photovoltaics on every surface, even North-facing, is the clear choice since ambient light still produces watts. Of the non-tracking schemes, the "wedge" shape yielded the least amount of energy loss with the most output but was subjectively evaluated as the worst architectural scheme. This was largely due to the odd overall shape as well as the small living area available that was above the 6' 8'' needed for comfortable headroom. Figure 11 shows the comparison of 6 of the final schemes with their ranks in the various evaluation categories.



SUMMARY OF SCHEMES/STRATEGIES (ordered by presentation)

Figure 11. Final summary evaluations of schemes as presented at the end of the term

## 4 CONCLUSIONS AND FUTURE DIRECTIONS

This exercise provided a rich opportunity to experiment with parametric modeling and the Solar Decathlon competition rules provided a well-defined pedagogical instrument for this introduction. By directly linking external data to the dimensions extracted from the parametric model, students gained a strong awareness of how a parametric model can increase the flexibility of early design efforts and how driving a design with a parametric model can both defer the final decision about a solution while offering very powerful and accurate evaluation of a design at any step in the process. As an instructional instrument, the tightly constrained design of an 800 square feet house that was required to produce more energy than it consumed provided a workable method to learn both principles of parametric modeling and net-zero design. The objective evaluation of cost, energy produced and energy consumed, forced students to be more creative in order to achieve a higher level of architectural character and boost their subjective scores. Some students who grasped the concepts early on were able to develop designs and models to a higher degree of sophistication including the modeling of structural beams that automatically increased their depth if the span increased. Likewise, some students developed portions of their in-

teriors, such as the kitchen, as a sub-sketch driven by the parameters of the larger, form sketch. One could immediately assess the functionality and spatial quality of the kitchen in each configuration since the rules for placing and modeling the appliances were incorporated into the kitchen sketch. If an overall configuration did create a crash of the appliances, the students could quickly consider alternative kitchen configurations and "remodel" their sketch. The schemes that reached the higher level of design development generally scored higher in the subjective categories as well. This may be due to the evaluators' ability to imagine themselves in the space where cabinetry is modeled. The lack of detail and human scale items like furniture in the less refined projects provided fewer opportunities to imagine the space populated with people, which in turn may have negatively affected their subjective evaluation.

There were both lessons learned from this exercise that may be worth repeating as well as improvements that could be made. Some of the key lessons were:

1. A very well defined, reasonably small project, like the solar decathlon house design, is an ideal way to introduce students to the concepts of parametric design. The limited solution set yields design results very quickly so that students can readily appreciate the strengths of a parametrically driven process.

- 2. Linking to external data provides accurate and authoritative feedback at any point in the process. This clarity and immediacy of feedback is a superior method for criticism and allows the student-teacher conversation to focus on generating more creative solutions.
- 3. Assigning a different conceptual scheme to each student at the beginning of a term accelerates the design process and eliminates the early search for the "best" concept. Furthermore, with radically different schemes in the studio being simultaneously explored, students are able to experience the challenges of alternative approaches. The assignment of a concept also removes some apprehension since the student is not held responsible if a concept simply does not work.
- 4. Assigning the conceptual scheme is likewise a drawback since young designers are eager to find the "magic bullet" scheme on their own. Motivating some of the students to adopt a predefined solution set can be a considerable challenge. It takes a more mature student to effectively work within that constraint.
- 5. The development of nested parametric models in a design yields the greatest educational benefit for the students. The additional experience in modeling and defining the drivers of design is invaluable and those students who were able to model at this level developed a stronger ability to think conceptually.
- 6. Greater rigor in evaluating emerging solutions subjectively throughout the term would provide a much richer design experience. If assessment of qualitative aspects of design were as readily available as the quantitative analysis of performance the student designs may have reached higher levels of detail.
- 7. While SolidWorks provided a good vehicle for this exercise, the software is uncommon in architectural practice. Students with significant skills in Rhino, SketchUp or Revit found it challenging to work in SolidWorks and often questioned its use in the studio.

The next steps will be to take the models to a much higher level of detail and attempt a similar process with other software such as Rhino or Revit. Applying the Net-Zero goal using software that students are more likely to encounter in practice may make the experience more relevant. Experiments integrating the same data set with the current version of Revit have already proved to be fruitful and the pedagogical instrument will be tested in an upcoming studio. While Revit does not currently integrate directly with Excel, experiments linking to Excel have occurred in firms such as Perkins and Will. Their direct integration of Excel as a bridge between Revit and Ecotect can provide the same pedagogical experience with real-time accurate analysis (Gutman et al. 2010). Utilizing software that students are already familiar with will accelerate the efforts in the studio since students will spend less time learning new software and more time developing their parametric rules and drivers of design.

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