EFFICIENTLY INTEGRATING SIMULATION INTO DESIGN: A CASE STUDY

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ABSTRACT

Simulators working within architectural offices are often met with simulation demands well in excess of their capacities. So that designers in those offices can make optimal decisions, simulators need to devise time-efficient methods of integrating knowledge generated by simulation into the decisions designers make. A key part of this process is communicating these results to designers.

This paper proposes one such approach in the context of a particular question: on which facades should glazing area be minimized or maximized? This question is examined by first creating a base model of a building typical of that constructed by our firm, and then parametrically varying the glazing ratio on each façade and simulating the resultant group. To enhance understanding, several characteristics of the base model are varied, and the process is repeated. Regression analysis is performed on the results of these simulations, and a novel plot design is developed with the intent of communicating the results to designers.

INTRODUCTION

The primary motivation for this study grew from the context in which the research was conducted: that of a single building simulator working within a medium-sized architecture firm. In this situation, the demand for simulation vastly outstrips capacity, and methods of incorporating simulation knowledge into building designs as efficiently as possible (in terms of simulator effort) are thus necessary.

This paper explores one such approach that begins with a design question which also sprung from the research's context: on which facades should glazing area be minimized or maximized? Within our firm, there are significant amounts of uncertainty regarding this question. As a result, designers either rely on one-off building simulations – which may or may not be available, given resources within the firm when design is taking place – or risk making sub-optimal decisions. This approach aims to examine this question via the parametric simulation of a theoretical building typical of the type our firm usually designs, and efficiently communicate the results to designers with the intent of enhancing their general understanding of this phenomenon.

Precedents for this work can be drawn chiefly from two areas of building simulation research: parametric regression/sensitivity analysis, and data display/visualization.

There has been much work done in the area of parametric regression and sensitivity analysis (see, as examples, O'Neill, Crawley, & Schliesing, 1991; Westphal & Lamberts, 2007; Purdy & Beausoleil-Morrison, 2001; Harputlugil, Hensen, & Wilde, 2007; Andarini, Schranzhofer, Streicher, & Pratiwi, 2009; etc). Although similar, the approach in this paper differs from these approaches in that it seeks to directly influence the design process by addressing a very specific design question and presenting the results in a manner easily communicable to designers.

There has been considerably less work done in the area of communicating simulation results to designers. The work that has been done (Prazeres & Clarke, 2003; Haberl & Abbas, 1998) provides some guidance in terms of graphical design principles, but has been primarily concerned with the communicating the results of a single simulation, as opposed to the results of a parametric study in which multiple simulations have taken place and need to be communicated simultaneously. The approach described in this paper is somewhat similar to that taken by design guides (ASHRAE, 2008; ASHRAE, 2007; CaGBC, 2004; NRC-IRC, 1997), but it's ultimately a more specific analysis; in many ways, it represents a compromise between a full building energy system and a design guide approach.

METHOD

The basis of this approach is to conduct multiple simulations of a theoretical building typical of what our firm usually designs while parametrically varying a characteristic of interest, and then summarize the results of the simulations in a way that will increase designers' understanding of this characteristic's effect on a building's energy consumption.

In this case, the parameters of interest were the glazing ratios of each façade. The process began with the development of the theoretical "base" building model. The EnergyPlus Example File Generator (US DOE, EERE) was used to generate a base model which was modified where necessary; the resultant building is described in Table 1, and shown in Figure 1.

Location
• Edmonton, Alberta
Architectural
• building footprint: 60 m × 20 m, oriented E-W • floor-to-floor height: 3.8 m • stories: 3 • conditioned area: 3600 m²
Building Envelope
Opaque wall sections • walls: steel stuf w/ exterior rigid insulation; U=0.28 W/(m²·K) ≈ R20 • roof: steel decking, rigid insulation, roofing membrane; U=0.16 W/(m²·K) ≈ R35
Glazing • triple-glazed, low-e, thermally-broken frame; U=1.74 W/(m²·K), SHGC=0.41, VT=0.55
Infiltration • peak rate (0.3 ACH) and schedule set as per EnergyPlus Example File Generator with "Office/Professional" building type
Internal Gains
• EnergyPlus Example File Generator "Office/Professional" building type "smart defaults" used for occupant (3.91 occupants/100 m²), interior lighting (10.8 W/m²), exterior lighting (W/m) and receptacle load (8.07 W/m²) intensities; gas appliance intensity set to 0 W/m²
HVAC
System • "Packaged VAV w/ Reheat" system type (selected from "90.1-2004 Appendix G Types" in EnergyPlus Example File Generator) ◦ supply fan static pressure: 500 Pa ◦ total fan efficiency: 70% ◦ cooling COP: 3.5 ◦ heating efficiency: 90%
Outdoor Air • Ventilation rates: 2.5 l/s/person + 0.3 l/s/m²
Daylighting
Daylight sensor/controls • Single daylight sensor in centre of each zone • On/off control with setpoint of 500 lux
Shading • Fixed exterior shading projecting from top of glazing added to E, W, and S facades w/ projection factors of 0.74, 0.74, and 1.00, respectively.

Table 1: base building description

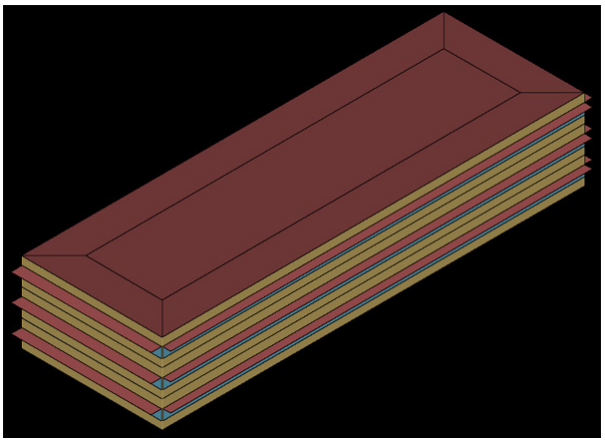

Figure 1: base building with 40% glazing ratio on all facades

A Ruby (Ruby Programming Language) script, gr.rb, was then used to manipulate the glazing ratios on each façade of the building to values of 20%, 40%, 60%, and 80%. Figure 2 shows illustrations of these facades. This resulted in a total of 256 (4^4) EnergyPlus input files, which were simulated using an EnergyPlus group simulation file also generated using gr.rb. Gr.rb then read the outputs of each of the 256 runs and produced a comma-separated output file that contained the glazing ratio combination, gas consumption, and electricity consumption for each run.

This process was then repeated seven additional times with a single characteristic of the base building being modified in each case. These cases are by no means exhaustive, but are meant to examine some of the more common design questions that designers in our firm encounter. They are described in Table 2.

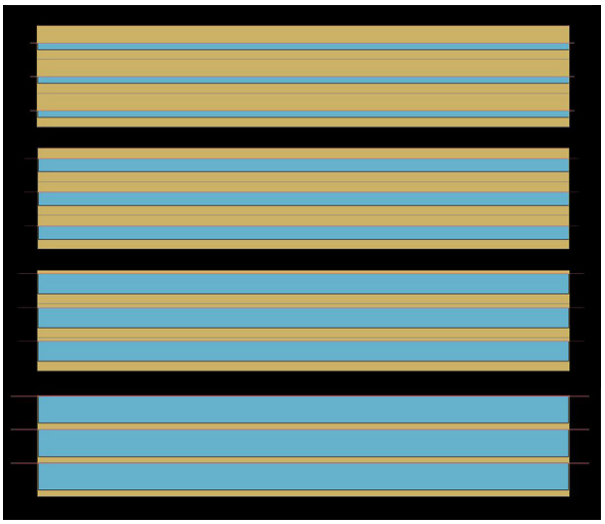

Figure 2: illustration of facades with glazing ratios of 20%, 40%, 60%, and 80% (from top to bottom)

case	description
0	base case
1	double-glazing case: all glazing changed to U=2.44 W/(m²·K), SHGC=0.45, VT=0.6
2	quad-glazing case: all glazing changed to U=0.78 W/(m²·K), SHGC=0.36, VT=0.48
3	no daylight sensors case (self evident)
4	Calgary case: Calgary weather file used
5	Vancouver case: Vancouver weather file used

Table 2: simulation case descriptions

To facilitate communication of these results to designers, the results summary files resulting from each case were then processed using two methods.

First, the glazing ratios of each output file were regressed on total (ie gas + electricity) energy consumption using Microsoft Excel, and the mean gas and electricity consumption for each case were calculated. Second, each output file was plotted using a custom plotting application, grPlot, created using Processing (Processing 1.0).

GRPLOT

The effective communication of simulation results to a relatively non-technical audience was a key goal of this work. To this end, a novel plot style was developed. It is essentially a modified "bubble plot," which is similar to a traditional scatter plot in which points are plotted on two axes, but differs in that the points themselves convey additional information.

In a bubble plot, the points are circles of varying radius, with the radius conveying a third dimension of information. In the method used for this paper, each character is comprised of four circles joined at a central point. Each circle's radius of corresponds to the glazing ratio on of the four facades. To assist reading the chart,

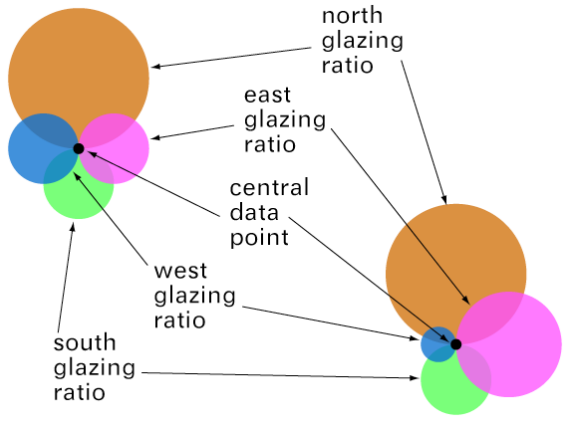

Figure 3: illustration of plot point design

each circle is plotted in a different colour. This scheme is illustrated in Figure 3.

GrPlot was created to automatically produce the plots described above.

RESULTS

The results of the regression analysis for each case can be found in Table 3. The mean annual gas and energy consumption for each case can be found in Table 4.

	regression coefficients			
case	GRN[1]	GRS	GRE	GRW
0	2.62	0.07	0.95	1.11
1	3.48	1.01	1.32	1.57
2	1.02	-1.07	0.34	0.49
3	2.86	0.31	1.03	1.19
4	2.51	0.01	0.90	1.02
5	1.80	0.69	0.82	1.01

Table 3: regression coefficients for each case

	mean annual consumption [GJ]	
case	gas	electricity
0	843.1	782.5
1	995.5	783.5
2	595.1	791.8
3	821.7	886.8
4	690.1	791.8
5	336.0	800.6

Table 4: mean annual gas and electricity consumption for each case

The p-values for all of the coefficients in Table 3 that indicate an effect on overall energy consumption (ie, every one except the south-façade coefficients in cases 0 and 4) were sufficiently low to indicate significance (the highest p-value among these coefficients was calculated to be 2.61E-28).

The plots for each case are shown below. They are organized in three "sets" of axis scaling to ease comparisons. The first set is comprised only of case 0, the base case, the second set is composed of cases 1, 2, and 3 (the building modification cases), and third set contains cases 4, and 5 (the cases with different weather files). Because of space constraints, the plots for cases 4 and 5 have been reduced in size.

[1] "GRN" refers to north facade glazing ratio, "GRS" to south facade glazing ratio, etc

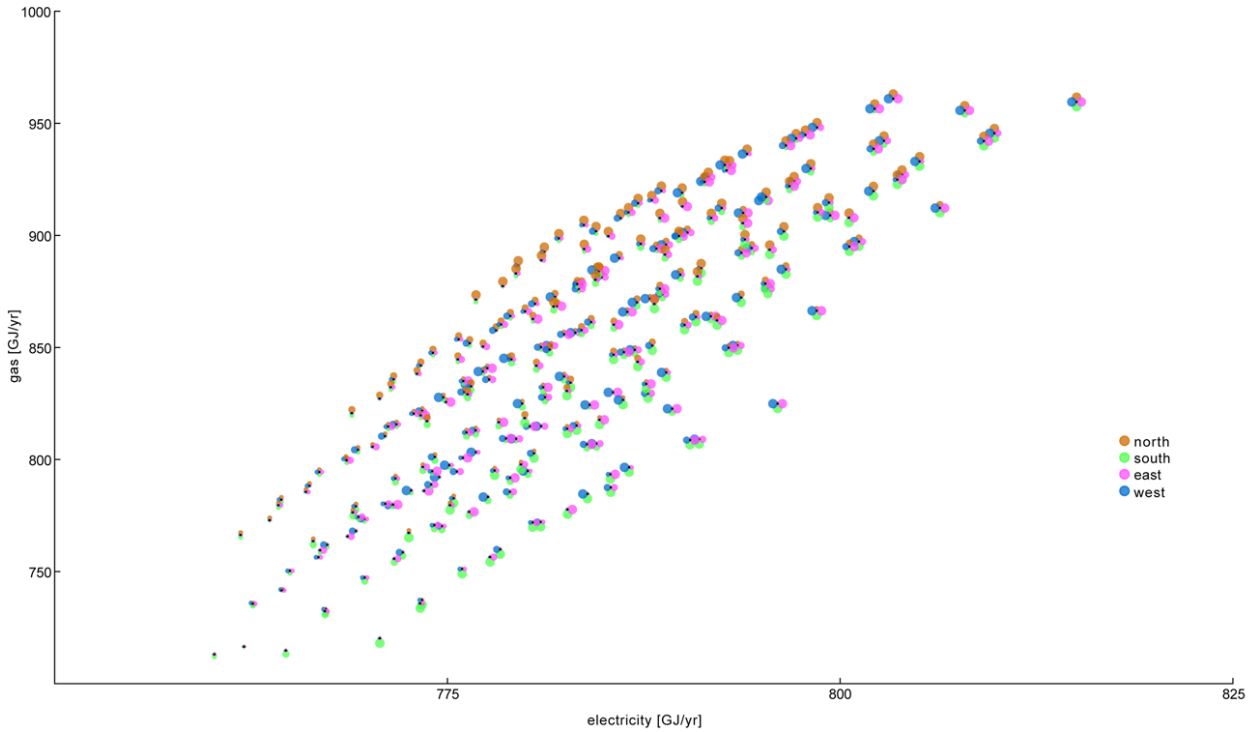

Figure 4: case 0 gas consumption, electricity consumption, and glazing ratios

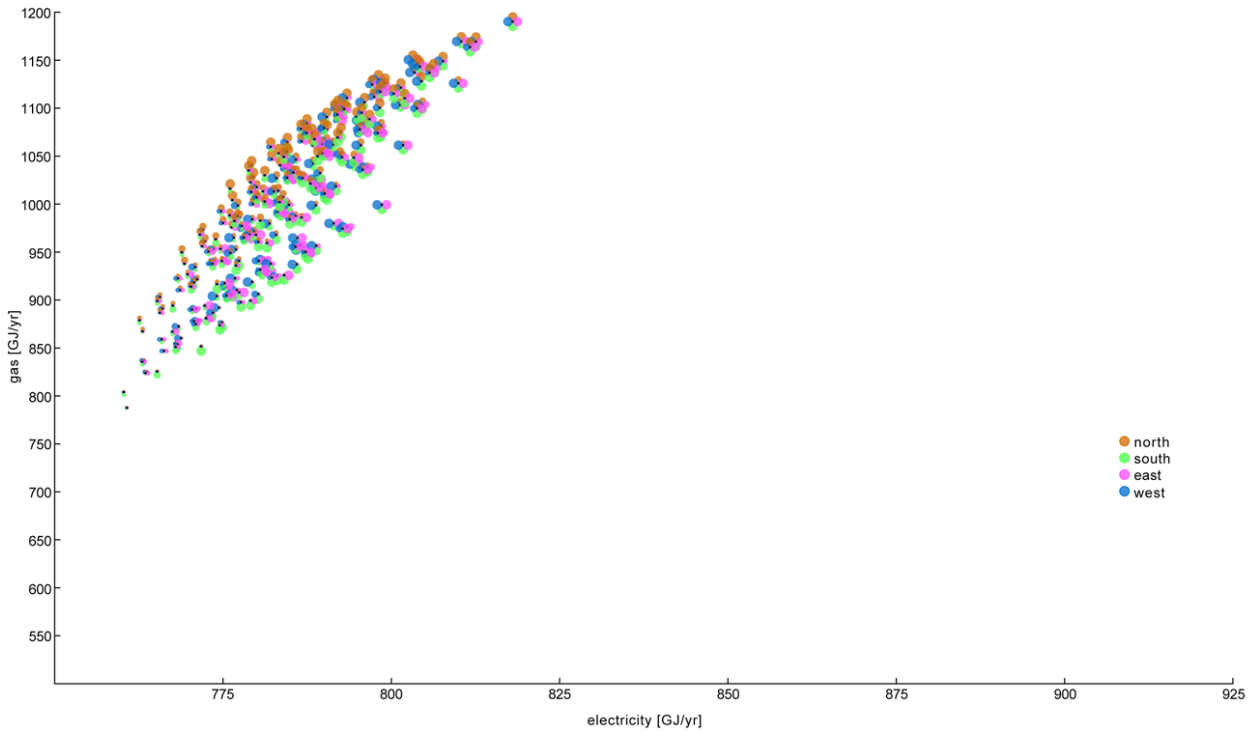

Figure 5: case 1 gas consumption, electricity consumption, and glazing ratios

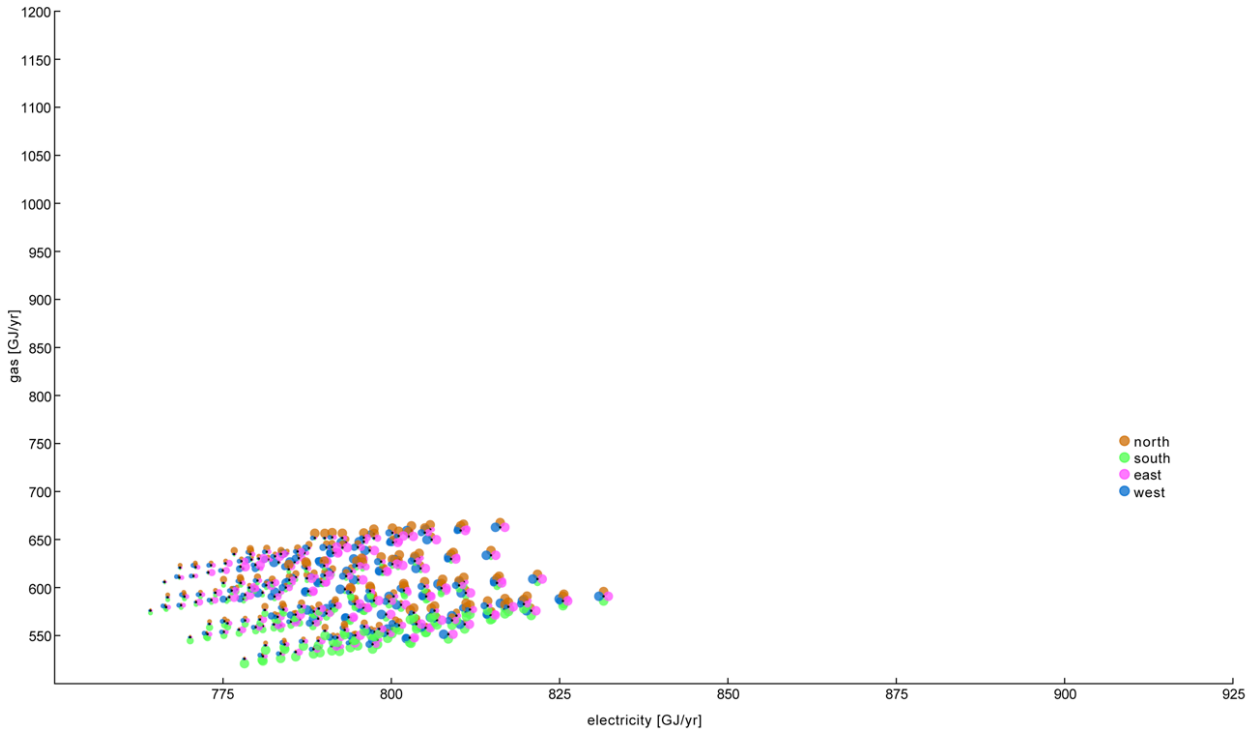

Figure 6: case 2 gas consumption, electricity consumption, and glazing ratios

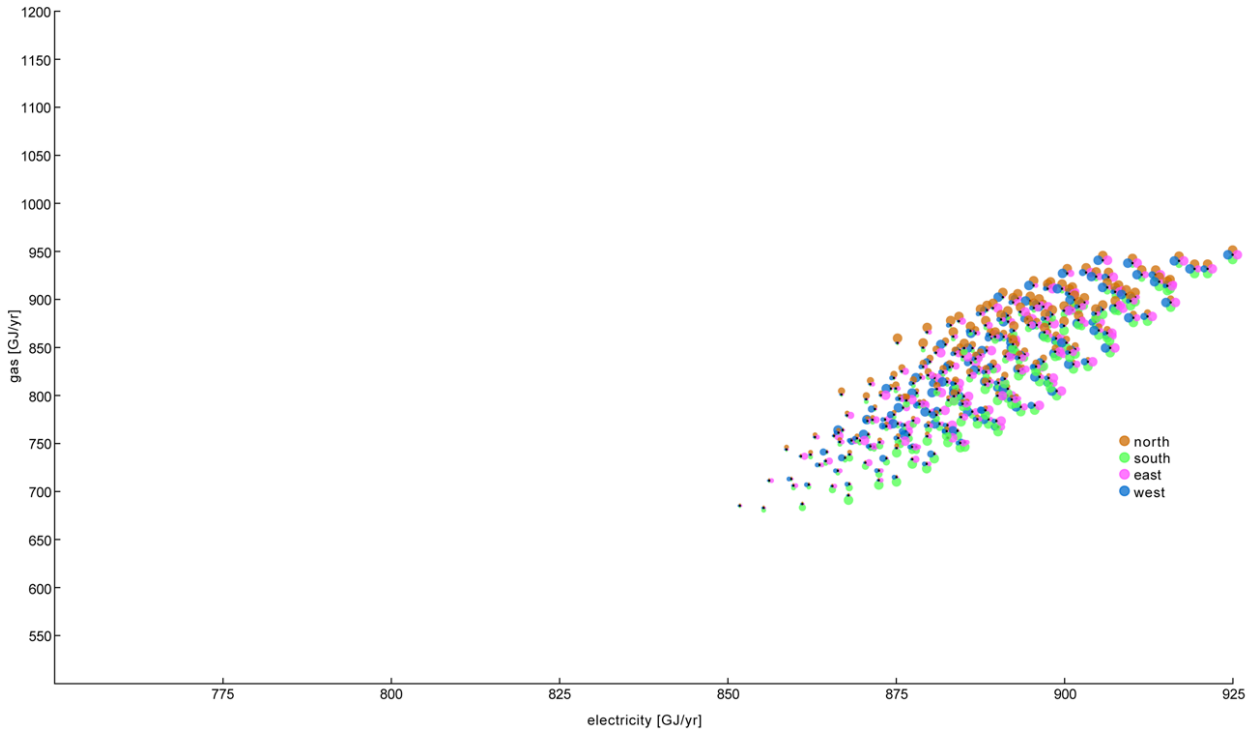

Figure 7: case 3 gas consumption, electricity consumption, and glazing ratios

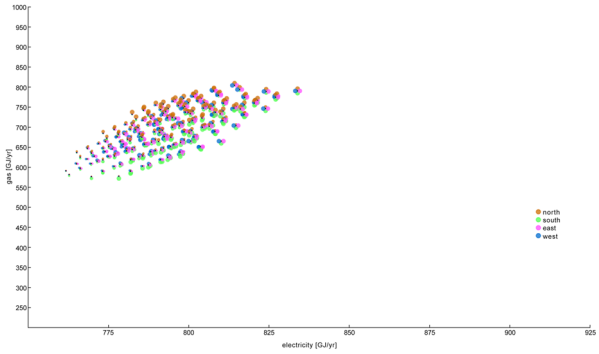

Figure 8: case 4 gas consumption, electricity consumption, and glazing ratios

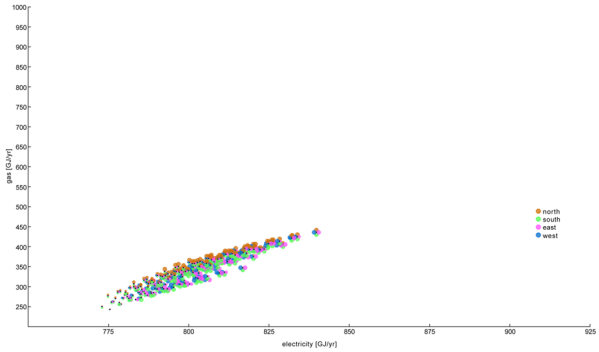

Figure 9: case 5 gas consumption, electricity consumption, and glazing ratios

DISCUSSION

Base case

The regression coefficients for the base case indicate that north-facing glazing has the strongest correlation with increased energy consumption, followed by east- and west-facing glazing, which have approximately equal effects. They also indicate that south-facing glazing has a weak or non-existent correlation with increased energy consumption.

These findings are illustrated in the base case plot (shown in Figure 4). There is a clear and pronounced increase in the size of the orange circles (those representing north-facing glazing ratios) as one moves from the "bottom" to the "top" the point cluster, and the largest orange circles are concentrated almost exclusively in the plot's upper-right quadrant. The green circles (representing south-facing glazing ratios), on the other hand, tend to grow as one moves from the "top" to the "bottom" of the point cluster, and show no such correlation in any quadrant. The purple and blue circles (representing east-facing and west-facing glazing ratios, respectively) don't show any pronounced trends aside from generally growing as they move in the direction of the plot's upper right quadrant in a fashion that shows very little differentiation from one another.

Increasing glazing tends to increase both gas and electricity consumption (although it appears to have a larger effect on gas consumption than on electricity consumption). While increased gas consumption was expected with larger glazing ratios, increased electricity consumption implies that the increased cooling loads that tend to result from higher glazing ratios more than offset any savings that result from increased daylight harvesting.

These results are possibly explained by the relatively low ambient temperatures experienced in Edmonton, which result in most insolation offsetting heating loads instead of creating cooling loads. In such a situation, more insolation generally means less energy, so that the façade that receives the most insolation (south) has the weakest correlation with total energy consumption, while the façade which receives the least (north) shows the strongest.

Building modification effects

Figure 5 and Figure 6 show the results from cases 1 and 2 (respectively), in which the triple-glazed windows of the base case were replaced with double-glazed and quadruple-glazed windows (respectively). The regression coefficients show that increasing glazing conductivity tends to increase the correlation between each glazing ratio and total energy consumption. This is echoed in the plots. The overall spread on the gas axis increases (relative to the base case) in case 1 and decreases in case 2. The spread on the electricity axis remains similar in all three plots.

One notable difference between these cases and the base case is the change in the correlation between south-facing glazing and total energy consumption. In case 1, the south-facing glazing ratio shows correlation roughly in line with that of the east- and west-facing glazing, while in case 2 south-facing glazing is negatively correlated with total energy consumption. This result is discernible with relative ease in the plot for case 2, but not immediately apparent in case 1. However, it can be seen when comparing, for instance, the lower-most four points, which in the base case share roughly the same gas consumption but show variation in case 1.

These results are likely due to the fact that the reduction in heat loss from a better-insulated window more than compensates for the slight reduction in thermal gains that result from increased SHGC of the quadruple-glazed window. This decreases the annual heating cost (or increases the heating energy benefit) that re-

sults from a given area of glazing, and thus reduces the correlation of this glazing with increased total energy consumption.

Additional cases were carried out in which the base building model's opaque wall conductances were increased and decreased. Because of length constraints these cases could not be included, but they appear to indicate that varying the ratio of opaque wall and glazed section thermal conductances produces results of similar character, regardless of if this variation is achieved by modifying the glazing or opaque wall.

Figure 7 shows the results from case 3, in which the daylight sensors of the base case were removed. In this case, the regression coefficients show an increased correlation between glazing ratios on all facades and total energy consumption. This is evident on the plot, which shows an increase in the mean and spread of the points on the electricity axis (relative to the base case). These results make intuitive sense: if the building is unable to harvest the increased daylight that results from higher glazing ratios, then an energy benefit of increased glazing is eliminated, and its relative annual energy cost increases.

Climate effects

Figure 8 shows the results from case 4, in which a Calgary weather file was used for the simulation. The correlation coefficients in this case indicate a weaker correlation between glazing ratios and increased total energy consumption (relative to the base case). This is shown in the plots, in which there is a smaller spread (and mean) of results on the gas axis. Interestingly, there is a greater spread of results on the electricity axis. This suggests that the argument presented above – Edmonton's generally low ambient temperatures make most insolation beneficial (energy-wise) – is well founded. In a climate that is very similar in most respects but with slightly higher ambient temperatures, increased glazing tends to have a less harmful effect on heating loads (thus decreasing the correlation with gas consumption), and a more harmful effect on cooling loads (thus increasing the correlation with electricity use).

Figure 9 shows the results from case 5, in which a Vancouver weather file was used for simulation. In this case, the correlation coefficients indicate a stronger correlation between south-facing glazing and total energy consumption, and a weaker correlation between the other orientations and total energy consumption (relative to the base case). This is shown in the plot's reduced spread on the gas axis. As in case 4, there is greater spread and a greater mean on the electricity axis relative to the base case, suggesting that lower ambient temperatures decrease the heating penalty and increase the cooling penalty of glazing. The points in this plot appear to exhibit a tighter correlation between gas and electricity consumption, which may result from the increased cloud cover in Vancouver relative to Edmonton or Calgary. Such an environment sees a higher fraction of diffuse light, which could reduce the relative importance of the orientation of glazing and increase the relative importance of simple gross glazing area.

Plot design

This plot design was devised to communicate the relevant findings of a very large dataset to designers in an easily understandable manner. It appears to do a reasonable job of conveying broad trends in the data (eg, the general correlation of increased glazing ratios with increased total energy consumption, obvious trends among individual glazing ratios, etc), and it also successfully communicates the scale the of the data, particularly when making comparisons amongst cases (although this is partially obscured by the axes scaling required to make the plots legible). Also, by directly showing a datapoint for every simulation, the plots more directly communicate the methodology that was used to create this data.

However, more subtle trends in the data are not always made immediately apparent – for example, the finding in the base case that south-facing glazing is not significantly correlated with total energy consumption, which would be very relevant for designers, is directly communicated by the regression coefficients but not directly apparent from the plot.

While this plot design isn't able to communicate all of the simulation information a designer could need to make informed decisions with respect to glazing area, it doesn't appear to obscure any data either. In this very specific context, the plots are a tool that can be used with other tools (ie statistics) to communicate simulation data to designers.

CONCLUSIONS

The conclusions will be separated into two categories that align with the areas this research was meant to address: the relationship between glazing ratios, orientation, and energy consumption, and the communication of simulation results.

Glazing ratios, orientation, and energy consumption

The above results show that for the building type examined (medium-sized commercial, built to current best-practices), increased glazing correlates with increased energy consumption, except in the case of south-facing glazing that has a low thermal conductance relative to the opaque walls with which it shares a façade. This correlation can be weakened by decreasing the thermal conductance of the glazing relative to the building's opaque walls. For buildings of the type examined, the increase in cooling loads that result from higher glazing ratios appears to be greater than the savings produced from daylight harvesting. In climates with lower ambient temperatures, there appears to be less of a heating penalty and more of cooling cost associated with increasing glazing ratios.

It is important to note that this research has focused exclusively on energy consumption, and does not account for the effects of daylight beyond the electrical lighting energy which it can potentially save. This research similarly does not account for other effects of glazing, which include occupant views, interior and exterior aesthetics, natural ventilation potentials, etc. Decisions which balance these factors are the domain of designers; the intent of this research was to explore a method of making simulation knowledge more accessible to these designers, to enable them to give energy consumption due consideration.

Simulation information communication

A novel plot design based on the bubble plot was developed to aid in displaying the data generated by parametric simulation. This design is arguably successful in communicating certain characteristics of the simulation data, but alone does not adequately convey all of the information a designer would need to understand the effect of glazing ratios on energy consumption. That said, this design does appear to enhance understanding in some respects, and thus further developing similar methods of visually communicating simulation results will be an area of future work.

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