ENCLOSURE PERFORMANCE VS. BUILDING FORM IN COLD-CLIMATE COMMERCIAL BUILDINGS – WHAT REALLY DRIVES ENERGY-USE?

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ABSTRACT

Designers today, in response to codes or voluntary "green building" programs, are increasingly concerned with Energy-Use Intensity (EUI) targets. Building form and building orientation may be powerful drivers of energy-efficiency – but few studies have quantified their effect. We designed a series of prototypical office buildings to show how much these and other architectural strategies reduce EUI in Toronto. Our eight prototypes ranged in gross floor area (12,000 sf to 160,000 sf) and plan form (square, slender, and H-shaped). We tested each with four levels of enclosure performance (code-compliant to very highperformance) and three window-to-wall ratios (20%, 40% and 60%). Setting climate-control systems as constants, we used eQuest to predict annual EUI and month-by-month end-use.

Plan form alone penalized EUI by less than 3%. Building orientation alone had a negligible impact. A 20% decrease in the window to wall ratio (WWR) reduced EUI by roughly 5%. Significant upgrades to the thermal resistance of the enclosure reduced EUI by nearly 40%. Applying all measures in concert had a cumulative - not a synergistic - effect, driving the EUI of an "exemplary" building to roughly 60% of the level predicted for a similarly-sized "market-level", nearly-code-compliant building.

INTRODUCTION

Recent history suggests that design teams will be challenged, with increasing regularity, to establish a target EUI for a project, to reach the target, and to have both their successes and failures made public. Several programs - legislative and voluntary - aim to lower the EUI of North American buildings, echoing the concerns of international policy agencies about the rising cost of fossil-fuel extraction, and the effects of greenhouse gas emission (IEA 2006, IPCC 2007). Although North American codes do not legislate EUI explicitly, as some European codes do, they are slowly ramping up related requirements. In Canada, the National Energy Code (which is invoked in the Ontario Building Code) requires that designers set a "%-better-than" EUI target, relative to an imaginary "reference" building, and prescribes minimum thermal resistance levels for enclosure elements and maximum WWRs, both of which vary with climate.

Meanwhile, some – but not all - voluntary "green building" programs reward designers' good intentions (if not actual results) with respect to energy conservation. The 2030 Challenge is exclusively focused on reducing greenhouse gas (GHG) emissions from fossil fuel use, setting aggressive targets tailored various U.S. locations. The U.S. Green Building Council's suite of rating products – the Leadership in Energy and Environmental Design (LEED©) labels – signify varying degrees of commitment to EUI reduction. PassivHaus, which demands post-occupancy verification of actual performance, has been used in the design and construction small and mid-sized commercial buildings in both North America and northern Europe. Both the AIA Top Ten Green Awards program and the U.S. DOE High Performance Database require that all of the projects they celebrate document EUI – through simulation, or fuel bills, or both.

Tracking the actual EUI of buildings over time also is gaining popularity. Many U.S. cities – New York City being the most conspicuous – have local bylaws that demand public reporting of the fuel use of individual buildings (NYC 2012, 2013). In Canada, a nation-wide coalition of office-building owners publishes summary data, in order to attract and retain major corporate tenants (REALPac 2010, 2012).

We studied the choices that lie within the architect's purview. Even though occupant behaviour drives actual EUI to a great degree, design determines the best that can be realized. Also, we suspect that the architecture either enables or constrains the design of energy-saving climate control systems. So, is there an ideal plan form and orientation for an energy-efficient building – in our climate? What is the maximum leverage that the enclosure can exert? Together, how much do all non-equipment measures drive EUI?

LITERATURE REVIEW

Olgyay's "Design with climate" is the seminal North American study. It recommends an ideal plan form – with respect to energy conservation, that is – for a 1-storey house (1,225 sf, or 14 m^2 in floor area). A slender plan, oriented with its long dimension running east-west is ideal in Miami, while a square plan, oriented slightly south-east is ideal in Minnesota (Olgyay 1963).

Although Olgyay did not estimate EUI in large buildings, his results seem to have had an influence on designers' perceptions about all buildings. Mazria (1979) calls the slender east-west plan ideal, and suggests that it applies to small commercial buildings (of unstated size) as well as to houses. Two agencies of the U.S. government, who construct large buildings, advocate the east-west plan (and the slender plan in any orientation) in preference to a more compact, square plan (US DOD 1987, USAF no date). The most recent echo of this idea, intended to apply equally to all small office buildings (up to 20,000 sf, or 1,980 m^2), in all North American climate zones, is shown in Figure 1 (ASHRAE 2004).

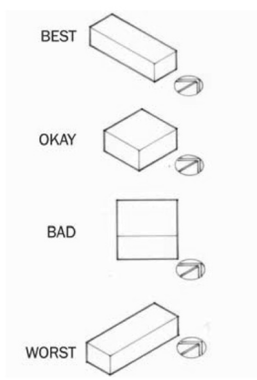

FIGURE 1: RECOMMENDED BUILDING ORIENTATIONS (ASHRAE 2004)

Dean (1981) declares that an architect's approach to the design of an office building is "necessarily unique" – that is, different than the approach to be used in the design of a house - but does not deem any strategy "good" or "bad" in either context. He also stops short of specifying whether it is building size, or use, or some combination that demands the unique approach. We noted, during visits to commercial buildings with impressively low fuel bills (in the Great Lakes Basin and U.S. Northeast) no wall greater than a nominal R-25 (RSI 4.40) and no roof greater than a nominal R-45 (RSI 7.92) (Ross 2009). Houses that meet standards such as R2000 and PassivHaus have walls typically at R-40 (RSI -7.05) and roofs at R-60 to R-80 (RSI 10.57 to 14.09). The commercial buildings that used less than 100 kWhr/m^2/year (less than 30% of the Canadian average) confirmed Dean's remark, but we wanted to know exactly why.

A group of private consultants that studied an office building, 25,833 m^2 (278,067 sf) in gross floor area, in Mississauga, ON, found that building orientation had no impact on EUI. It also found that building form drove total annual EUI much less than it did heating and cooling loads, hinting at the significance of the internal loads in an office building - most notably lighting (HFP 1980).

HFP simulated the office building with enclosure elements whose thermal properties fell between the Ontario Building Code minimums and better practice that was typical in provincial government buildings at the time (see Table 1). Our study simulated buildings with better-performing enclosures, because the requisite elements are readily available today (see Table 2). Advances in window technology are key.

	WALL	**ROOF**	**WINDOW**
	Nominal Rimp		Nom. Uimp
OBC 1980	R-8	R-14	
HFP sims.	R-12	R-12	Uimp 0.49
Province 1980	R-20	R-20	

TABLE 1: THERMAL PROPERTIES OF ENCLOSURE ELEMENTS USED IN HFP 1980

We found no study measuring the impact of building form and orientation across a range of typical building sizes. Thus, the design of our study became quite significant. Using one building type (offices) in one climate (Toronto), we hoped to establish a framework that other researchers could re-use to study other building types, in other climates. Although a single simulation never predicts the EUI of a real-life building with pinpoint accuracy, we expected that comparing a large number of simulations, all made with a consistent set of assumptions, would reflect the power of each parameter with a reasonable degree of reliability. Such a comparison would give architects a clearer perspective than the design guides have done, to date. Our observations, therefore, focus on the delta between one simulation and the next. We also compared the results generated by three simulation tools – to discover whether all predicted the same trends, and to see how much difference there is when three tools simulate the same building.

STUDY DESIGN

In planning our series of simulations, we wanted to know:

- Are there really, as the ASHRAE guide suggests, building forms and orientations that are, in their essence, “bad” and “worst”? What limitations on EUI reduction would this place on a building on an urban site that is constrained in its form and orientation?
- What defines the threshold between a “skin-dominated” building and an “internal-loaddominated” building? Should designers of commercial buildings, as our tours seemed to suggest, avoid the very high levels of insulation than designers of high-performance houses use?
- Does our climate – that is, if Olgyay is correct, our latitude – suggest “OK” and “best” strategies?
- Would 3 selected simulation tools make the same estimate of the EUI of a given building?
- How much do building form, building orientation and the design of the building skin each drive EUI? How much can they achieve if applied in concert? How does this relate to the targets set in the various energy-efficiency and GHG reduction programs being considered today?

We designed 8 prototypical plans (square, slender and H-shaped) at 3 sizes. Our small building has a gross floor area of 12,000 sf (on 2-storeys); our medium and large buildings are 50,000 sf (4-storeys), and 160,000 sf (8-storeys), respectively. We gave those that are oriented eastward the tag “HE” or “EW”, and rotated the 5 plans that have an intrinsic orientation by 90º, calling those “HN” or “NS” – as shown in Figure 2.

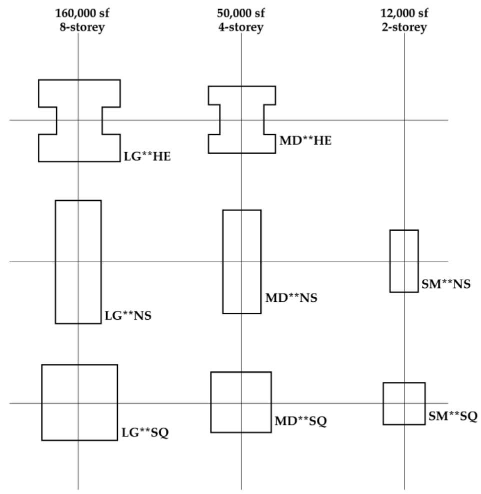

FIGURE 2: EIGHT PLAN FORMS USED IN THIS STUDY

We set the following as constants: occupancy schedule (weekdays), floor-to-floor height (13’-6”), lighting and equipment power densities (1.3 W/sf, 1.5 W/sf), and no use of lighting controls. (All inputs are documented in Ross 2009). To minimize the impact of varying the climate control systems from one size of building to another, we set the heating system to electric resistance for all simulations. Cooling systems were packaged single-zone DX coils, with air-cooled condensers (EER 8.5), auto-sized by the software. We proved our floor plates realistic, establishing a core with elevators, exit stairs, washrooms and service spaces all sized appropriately for each building, making sure each plan would accommodate at least two alternate tenant layouts. We allocated space to private offices, open-plan offices, and all other spaces consistently, and used the drawings to establish the inputs to the simulation software (see Figure 3).

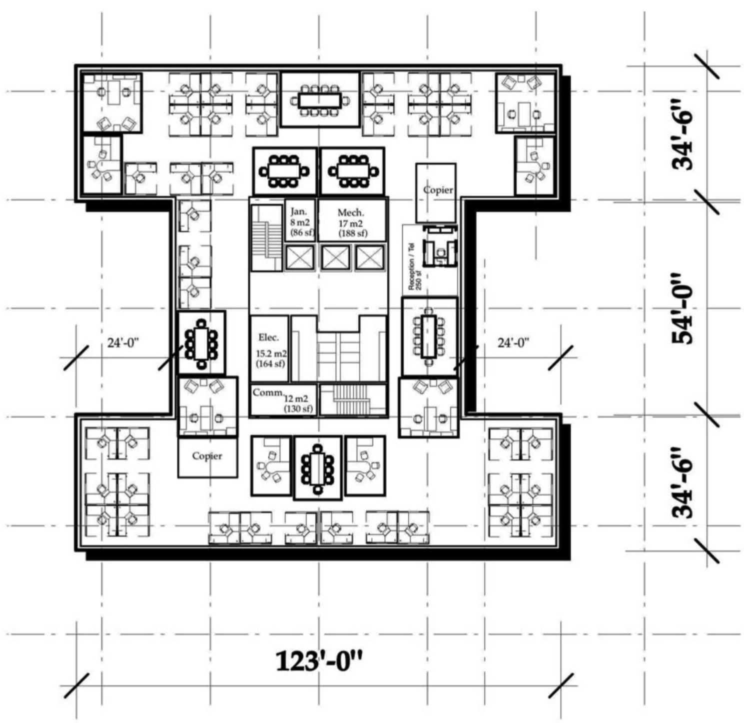

FIGURE 3: MEDIUM H-SHAPED PLAN FORM, EAST-FACING NOTCH (MDHE-*)**
(FOOTPRINT 12,537 SF @ 4 STORIES = GROSS FLOOR AREA 50,148 SF)

We varied the window-to-wall ratio (WWR) from 20% to 40% and 60% to represent three designs in common use, and we specified four realistic enclosure packages (see Table 2).

		EFFECTIVE WALL	ROOF	FNDTN.	Uimp	WINDOW SHGC	VLT	Air changes (ACH)	Corresponds to
Market	**D**	R-8	R-5	none	0.55	0.72	0.81	0.90	slightly below OBC 2006 min.
Institutional	**C**	R-17	R-19	vert. int'r 2'	0.34	0.63	0.73	0.50	typical of School Boards ca. 2008
High Performance	**B**	R-24	R-33	vert. int'r 4'	0.35	0.46	0.62	0.30	similar to many on US DOE database
Exemplary	**A**	R-36	R-48	full u/s	0.21	0.30	0.60	0.10	lowest EUI toured & at eQuest limits

TABLE 2: THERMAL PROPERTIES OF ENCLOSURE ELEMENTS USED IN THIS STUDY

Thus, the study would consist of all of the permutations and combinations of the architectural parameters. That is, one simulation was run for each combination of 13 plan forms x 4 enclosure types x 3 WWRs = 156 runs. We chose eQuest 3.0 as our principal tool because it accepts a comprehensive set of inputs. We confirmed that it converts thermal resistance values from nominal to effective fairly. We also repeated roughly 25% of our simulations using MIT Design Advisor and the NRCan Screening Tool (see Verification of simulation outputs, below.)

DISCUSSION

We expected EUI to be highest in the small buildings, because of their relatively high surface area to volume ratio. As long as comparisons were made within a single size class (SM, MD, or LG), we expected that EUI would rise as WWR ratio increased. We organized our 156 combinations into a matrix according to these expectations (see Figure 4), predicting that a group of very low EUI types would cluster near LG20 (at the extreme lower left), and a group of very high EUI types would cluster near SM60 (at the extreme upper right). Our simulations would show the trends, across the other fields.

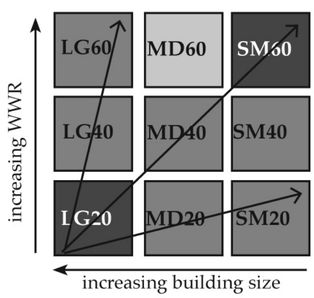

FIGURE 4: MATRIX OF 156 RUNS: EXPECTED TRENDS

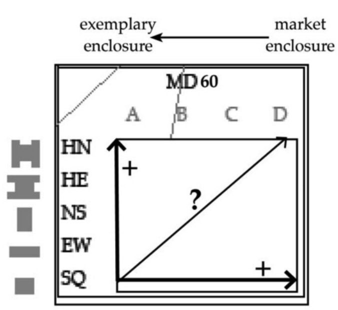

FIGURE 5: EXPECTED TRENDS: ENCLOSURE VS. PLAN FORM FOR ANY SIZE/WWR SET

We also predicted the pattern within any of the squares in Figure 4. As the enclosure was down-graded from "exemplary" to "market", or as the plan form was changed from square to an H-shape, we expected EUI to rise. The simulations would quantify the EUI for each permutation and show whether there are straight-line trends, as shown in Figure 5. The EUI generated by eQuest for all 156 simulations is shown in kWhr/m²/yr, in Table 3.

window to wall		LARGE 160,000 sf, 8-storey 161,312 sf = 14,986 m2				MEDIUM 50,000 sf, 4-storey 50,176 sf = 4,662 m2				SMALL 12,000 sf, 2-storey 11,858 sf = 1,102 m2			
		LG				MD				SM			
		A	B	C	D	A	B	C	D	A	B	C	D
60%	HN	159	185	200	244	182	211	226	275	-	-	-	-
	HE	159	184	199	242	181	210	225	273	-	-	-	-
	NS	155	179	195	238	178	207	223	270	204	240	254	315
	EW	154	178	193	234	174	201	216	263	203	236	250	310
	SQ	156	178	196	238	172	199	215	259	204	238	253	316
40%	HN	153	176	192	235	173	200	216	263	-	-	-	-
	HE	152	175	192	234	172	199	215	263	-	-	-	-
	NS	148	172	187	230	169	196	212	260	193	224	241	303
	EW	147	170	186	226	168	194	210	256	193	223	239	299
	SQ	150	173	189	231	164	190	207	251	194	224	240	299
20%	HN	147	167	185	228	164	189	207	254	-	-	-	-
	HE	147	167	185	228	164	188	207	254	-	-	-	-
	NS	142	164	181	223	161	186	205	251	183	213	234	294
	EW	142	163	180	220	161	184	202	248	183	212	232	291
	SQ	143	164	182	225	158	182	200	244	186	215	235	288

TABLE 3: TOTAL ANNUAL EUI AS SIMULATED BY EQUEST (KWHR/M²/YEAR)

The overall array was as predicted (as in Figure 4). The large, square building with 20% WWR and the highest-performing enclosure (LG20SQ-A, at the lower left) had 45% of the EUI of the small, slender building with 60% WWR and the lowest-performing enclosure (SM60NS-D, at the upper right).

The combined effect of using all of our architectural strategies in one design can be seen in the runs that fall under either the “large”, “medium” or “small” column. The least energy-intense type used between 57% and 59% of the energy used by the most energy-intense type (e.g. LG20SQ-A vs. LG60HN-D).

Within each box (as in Figure 5), our predictions also came true. When we kept the building size and WWR constant but varied the building shape and enclosure, the EUI for the most conserving building was consistently 62% to 63% of the EUI of the least conserving building. The trend from lowest to highest EUI followed a fairly straight line, from lower left to upper right within each box, as we expected.

Building size had a notable impact, on its own. Our medium-sized buildings used 85%, and our large buildings 77% of the energy small buildings with the same plan form, building orientation, and skin design (e.g. MD60EW-C of LG60EW-C vs. SM60EW-C).

Building form, on its own, had little effect. The ratio “other shape to SQ” was 0.97 to 1.03 in 82% of the simulations (e.g. LG60HN-D to LG60SQ-D), as long as all other parameters were kept consistent. In the medium-sized buildings, EUI was 4-6% larger in the H-shaped building than in the square building. We think all of these values lie well within the margin of error of the software.

Building orientation had next to no influence on EUI. Only in a few medium-sized and small buildings with 60% WWR, did the simulated east-west building appear less energy-intense that the north-south building – and by just 2-3% (again, well within the margin of error of the software).

Window-to-wall ratio (WWR) reduced EUI more than building form or orientation. Changing the WWR from 60% to 40% reduced the energy-intensity to 0.93 to 0.97 of the initial value. Reducing the WWR further, to 20%, reduced the EUI to 0.89 to 0.94 of the initial value. Thus, we may say that a 20% change in WWR yields roughly a 5% change in EUI, if all other parameters are kept constant.

Enclosure specification showed the greatest potential of any strategy, acting alone. A building with an "exemplary" (A) enclosure drove EUI to 0.65 of that of the same building with a "market" (D) enclosure. A less extreme improvement - changing from "institutional" (C) to "high-performance" (B) - reduced EUI to 0.90 to 0.94 of the "C" value – just as much as changing the WWR from 60% to 20%.

"Skin-dominated" or "internal-load-dominated"?

Figure 6 shows the month-by-month end-use profiles (from eQuest) for three versions of the same medium-sized building with a square floor plate and 40% WWR. Internal loads - area lighting, task lighting and desktop equipment (i.e. plug loads) – used the same amount of energy in all three cases. As the enclosure specification is varied, energy used to heat or cool the space decreases enough that this building, which is "skin-dominated" when in has a "market-level" (type –D) enclosure, becomes "internal-load-dominated" when an "exemplary" (type –A) enclosure is applied.

With the A enclosure, less energy is needed for heating and cooling than is needed for plug loads and area lighting. Our "exemplary" walls and windows, though not as exemplary as those normally seen in very high-performance houses, have brought this office building to the point where further reductions in EUI should be sought through by addressing lighting and plug loads, and climate control systems.

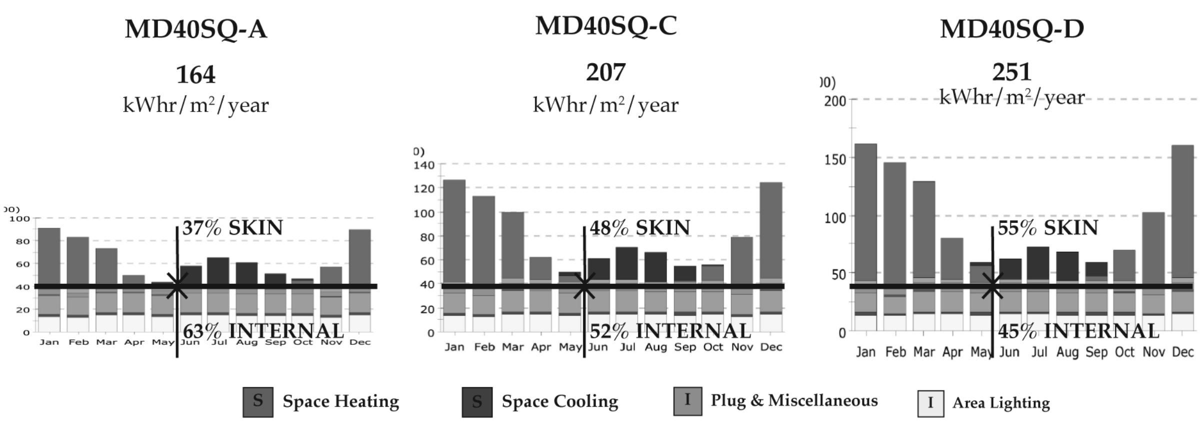

FIGURE 6: END-USE PROFILES FOR A SQUARE BUILDING WITH "EXEMPLARY" (LEFT), "INSTITUTIONAL" (CENTRE) AND "MARKET" ENCLOSURES

Building orientation and climate

We wondered whether the slender east-west building seems "good" to some, because it can capitalize on south-facing windows for solar gain, in the way that Olgyay's cold-climate houses did. We also wondered whether the “good” building was perhaps “particularly good” in one climate and “less good” in another. Using the medium-sized slender floor plan, with an “institutional” (-C) enclosure, and 60% WWR on the long sides only, we ran another set of simulations in various North American climates, changing the building orientation from "bad" to "good" (as in Figure 7).

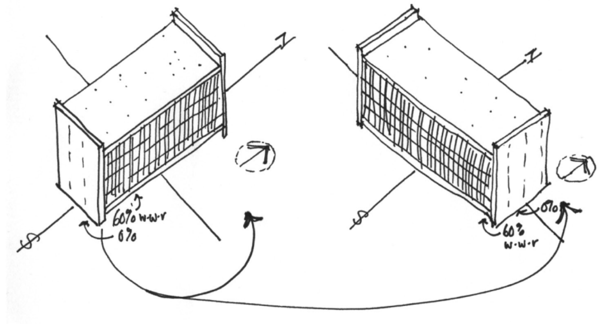

FIGURE 7: “BAD” (LEFT) AND “GOOD” (RIGHT) VERSIONS OF THE MD-C BUILDING

	latitude	Energy Intensity (kWhr/m2/yr) spine NS glass E&W	spine EW glass N&S	difference (% of high)
Regina	50°N	250	241	**-3.7%**
Seattle	47°N	164	157	**-4.5%**
Toronto	44°N	219	213	**-2.8%**
Phoenix	33°N	219	193	**-13.5%**
Miami	26°N	221	199	**-11.1%**

TABLE 4: EUI OF THE VARIATIONS IN FIGURE 7 IN VARIOUS CLIMATES

At northerly latitudes, the EUI changed little as the building was rotated 90° (as in our earlier simulations). Further south, however, the east-west building used significantly less energy than its northsouth equivalent (see Table 4). The east-west building is “good” in Phoenix and Miami, largely because it avoids punishing solar gains at sunrise and sunset. It is neither “good” nor “bad” in Toronto, where keeping the heat in is, within the limits described above, the principal way architects can lower EUI.

Verification of simulation outputs & limitations of the software

A second researcher worked independently at a remote site, using our inputs to create a second set of outputs in eQuest. This would have detected data-entry errors or attempts to simulate nonsense parameters. We found neither; the figures generated by both researchers were identical (Ross 2009).

We used the MIT Design Advisor and NRCan’s Screening Tool to twice re-simulate roughly 25% of the permutations (MIT Arch 2009, NRCan OEE 2007). Using Design Advisor, we varied the form, orientation, WWR and enclosure, but could not detail the space allocation (which determines lighting and plug loads) or specify the climate control systems to the extent we had in eQuest. Using NRCan’s Screening Tool, we could not vary building form or orientation, but we could make most other inputs. Neither of these tools discloses how it translates nominal to effective thermal resistance.

Inputs to all three software programs excluded site lighting, energy used to run elevators, standby losses, conditioning of basement and penthouse spaces, and operator error. The absolute EUI outputs, therefore, are lower than the real-life fuel bills for such buildings would be.

The patterns of “high” and “low” that we saw in the outputs from MIT Design Advisor and NRCan’s Screening Tool were consistent with the patterns we observed in our eQuest outputs, but the absolute values differed considerably from one tool to the next. When we compared the outputs of three programs simulating the same building, a 20% deviation occurred more than half of the time (see Table 5).

MIT Des. Adv.				NRCan Screening					eQuest			
A	B	C	D	A	B	C	D		A	B	C	D
213	**199**	**233**	**274**	**170**	**232**	**327**	**x**	**MD40NS**	**193**	**224**	**241**	**303**
212	**193**	**228**	**270**	**z**	**z**	**z**	**xz**	**MD40EW**	**193**	**223**	**239**	**299**
215	**193**	**227**	**267**	**163**	**215**	**297**	**x**	**MD40SQ**	**194**	**224**	**240**	**299**

TABLE 5: EUI (KWHR/M^2/YR) FOR MEDIUM BUILDING, 40% WWR, FROM 3 SIMULATION TOOLS

Design goals: comfort, peak power demand and EUI targets

Our models included temperature set-points to keep occupants comfortable most of the time. However, in our slender building with a 60% WWR, workers might experience unacceptably high temperature gradients and excessive glare on sunny days. We found that the most effective exterior sunshades we could design did not reduce annual EUI - in Toronto, that is. Exterior sunshades tailored to sun angles in Miami reduced EUI there by just 3 to 5%. Nevertheless, sunshades would improve comfort, by reducing glare and localized over-heating – and so ought to be considered when completing a real-life design.

We did not examine hourly peak electrical demand, as we felt we needed to help architects focus on reducing the EUI of their designs immediately. In our fieldwork, we saw an eightfold gamut between the EUI of code-compliant buildings and that of their high-performance counterparts. While peak demand is an important consideration, enough EUI reduction by enough buildings could begin to address it.

Setting an appropriate EUI target requires the judgment of a team of architects and engineers, taking all of the factors in a given scenario into account. Table 6 proposes some order-of-magnitude values for a Toronto office building, taking cues from current programs, and our own observations in the field.

Existing EUI:			
E1	Ontario average (NRCan 2002)		464
E2	REALPac Cdn. mean in 2009 (2012)		309
Simulations suggest achievable NOW:			
A	Using architectural measures only	60%	279
Alternative EUI Targets:			
T1	2015 (REALPac "20by15" Target)		215
T2	2015 (2030 Challenge as if EUI in E1=GHG emiss)	30%	139
T3	Lowest EUI office buildings in field studies (Ross 2009)		50-100
T4	2030 (2030 Challenge as if EUI in E1=GHG emiss)	0%	0

TABLE 6: ALTERNATIVE EUI TARGETS FOR AN OFFICE BUILDING IN TORONTO (KWHR/M^2/YR)

To the Ontario average (E1), we've applied the observation that an "exemplary" enclosure design drove our simulated EUI to 60% of a "market"-level building. The resulting 274 kWhr/m^2/yr (at line A) puts the power of the architectural measures in context, and shows the extent to which other measures must be employed, to achieve the profound economies that some design teams have already realized (T3).

CONCLUSIONS

In Toronto, the idea that there are "good" plan forms for lowering the EUI of an office building is a fallacy – as long as WWR is less than 60% and today's codes are met. In our simulations, plan form alone penalized EUI by no more than a 6%. This is good news for architects who wish to provide occupants with daylight and views of the outdoors, by using a slender or notched floor plate.

The notion that there are “bad” building orientations also is a fallacy – at all latitudes in Canada, that is. Building orientation had a negligible impact, in our study and others. Notwithstanding the statements made frequently in the green building literature, our findings are consistent with the findings of private consultants (HFP 1980), with the principles expressed in at least one design guide (Dean 1981) and with our observations of high-performing commercial buildings in the Great Lakes Basin and U.S. Northeast (Ross 2009). This is also very good news for any Canadian architect working on a constrained site where an east-west building orientation is unachievable, or undesirable for urban design reasons.

The EUI of our Toronto office building was driven mostly by the enclosure. As Olgyay advised, the further one moves away from the equator, the more thermal effects dominate (1963). Significant upgrades to the thermal resistance of the enclosure reduced EUI by 40%. A further 5% reduction in EUI occurred with each 20% decrease in the window to wall ratio (WWR). Applying all of architectural measures in concert had a cumulative - not a synergistic - effect, driving the EUI of an "exemplary" building to roughly 60% of the level predicted for a similarly-sized "market-level", nearly-code-compliant building.

Our results show that the terms “skin-dominated” and “internal-load-dominated” do not correlate with building size, shape, or type, and show how the design of an office building is necessarily different than that of a house. Our “exemplary” enclosure elements (which are readily available to any builder today) bring the cold-climate office building to a point where further EUI reductions are best sought in the design of climate-control equipment and lighting control devices, and by managing plug loads.

Today’s software programs do not predict the absolute EUI of a building accurately. The 20% spread we saw between the outputs of three programs estimating EUI in the same building has made us extremely wary about accepting any future stand-alone simulation as a reliable prediction of the eventual, real-life performance of a building. That said, the patterns were similar when we compared a large array of outputs from all three programs: the influence of building orientation and form on the EUI of a cold-climate office building is negligible.

Further studies, of similar scope, but concerning other common commercial/institutional building types - such as schools, public assembly buildings, etc. would be very valuable. Meanwhile, we hope our conclusions will help consulting architects and engineers design with energy in mind.

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