Integrative Solutions Group Inc.
Solving complexity in built environments

Energy and Form in Commercial Buildings

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Fixed Area Proportion Study

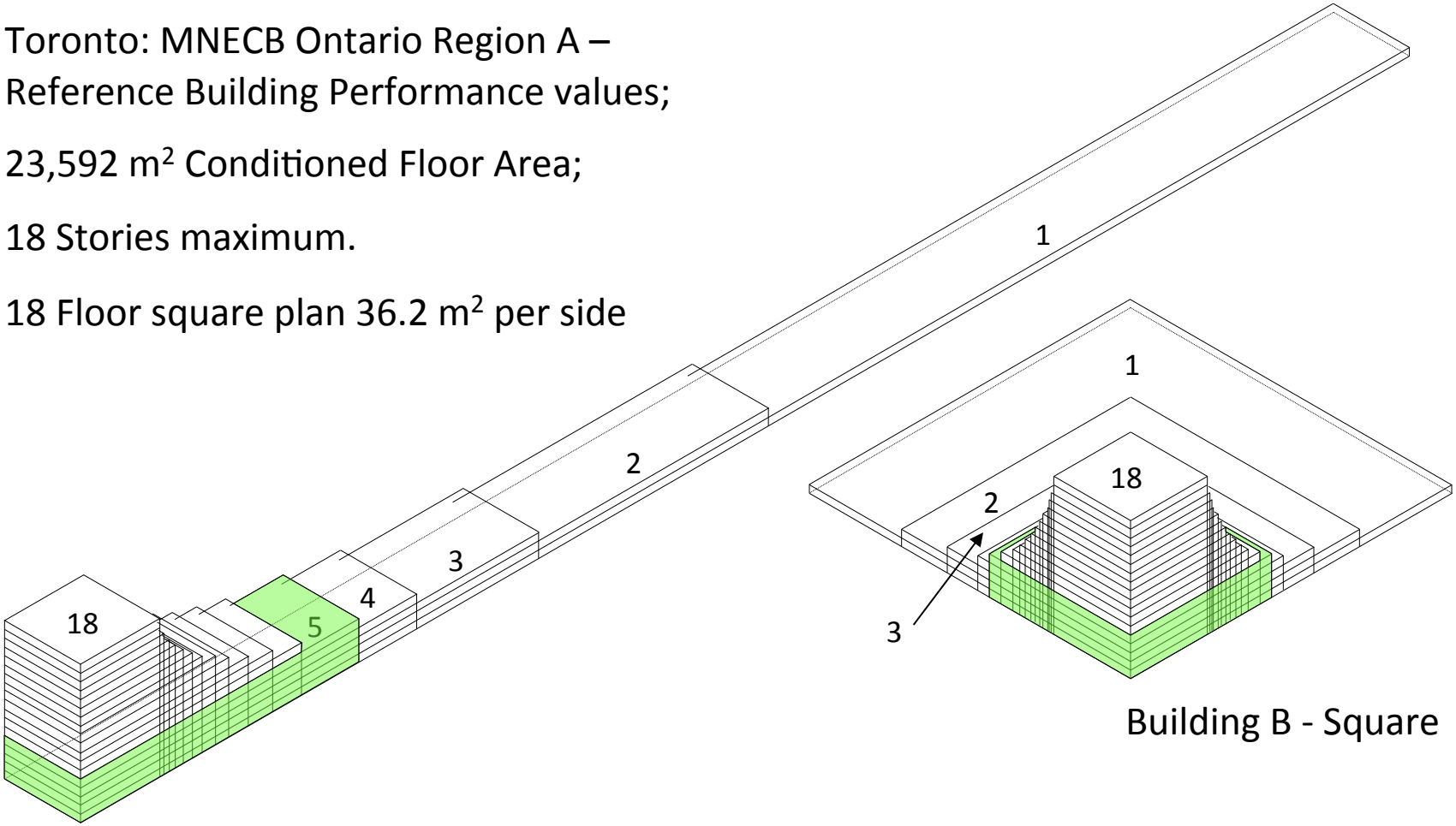
Office Occupancy;

Toronto: MNECB Ontario Region A –
Reference Building Performance values;

23,592 m^2 Conditioned Floor Area;

18 Stories maximum.

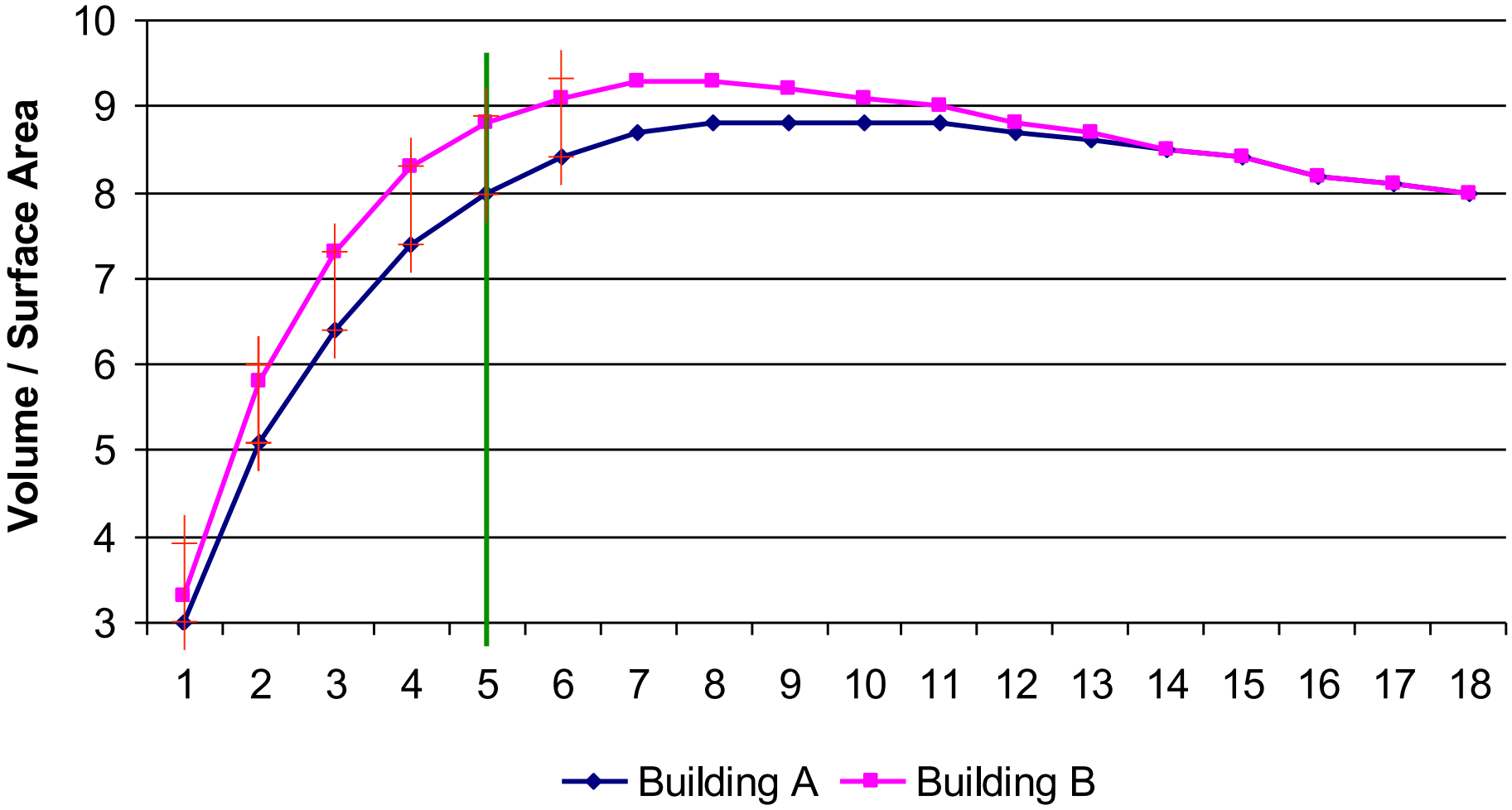
18 Floor square plan 36.2 m^2 per side



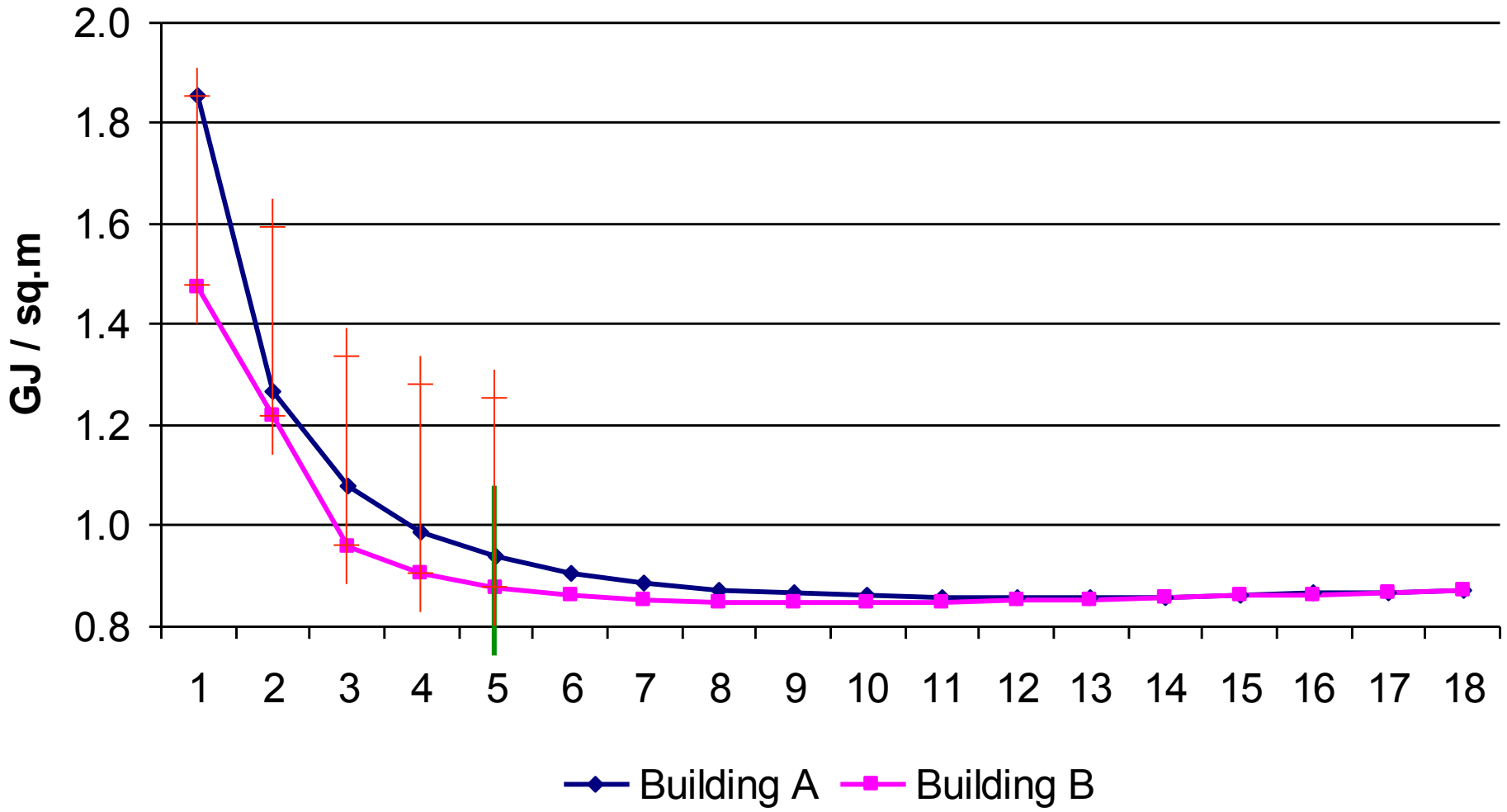
Building A - Rectangle

Building B - Square

Volume to Surface Area Ratio



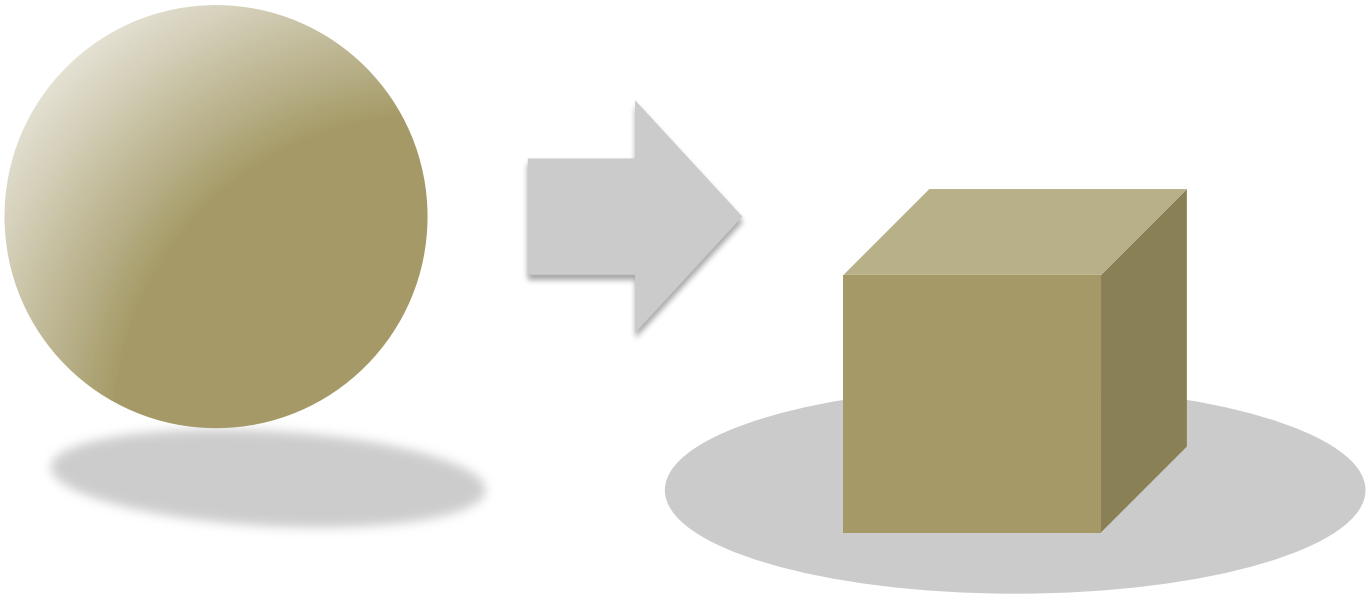
Energy Intensity



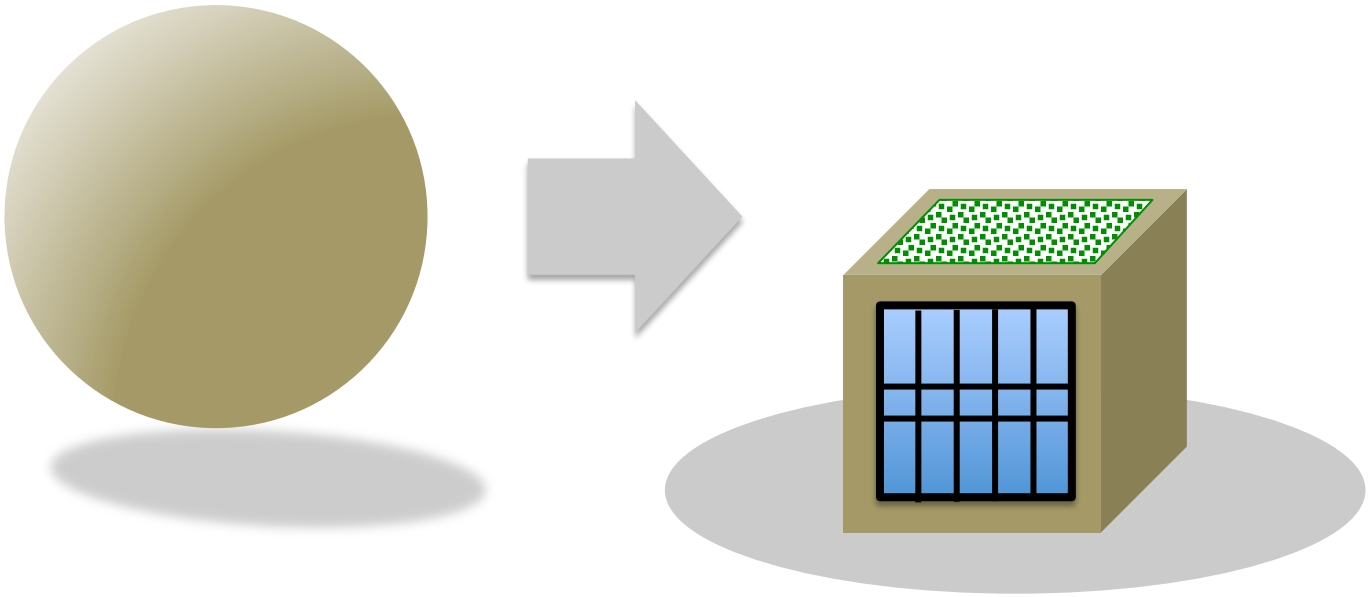
Observations from the fixed area test

- Rectangular plans have a lower Volume to Surface (V2SA) ratio, and higher unit area energy intensity than square plans;
  - V2SA ratio difference is inconsequential by floor 14;
  - Energy intensity difference is inconsequential by floor 11.
- Maximum difference in V2SA ratio occurs at floors 3 and 4;
- Maximum difference in energy intensity between the square and rectangular plan occurs at ground floor:
  - 380 MJ/m2 (106 ekWh/m2) for a 1 storey building;
  - 47 MJ/m2 (13 ekWh/m2) difference at 2 storey building;
  - 117 MJ/m2 (33 ekWh/m2) difference at 3 storey building;
  - 58 MJ/m2 (16 ekWh/m2) difference at 5 storey building;
- Energy impact of V2SA ratio:
  - Is not consistent or linear;
  - Is negligible in this test beyond a 9 storey building height.

Efficient Shapes (!?!)



Efficient Buildings (!?!)



Abandon “Form-based Energy Rules of Thumb”

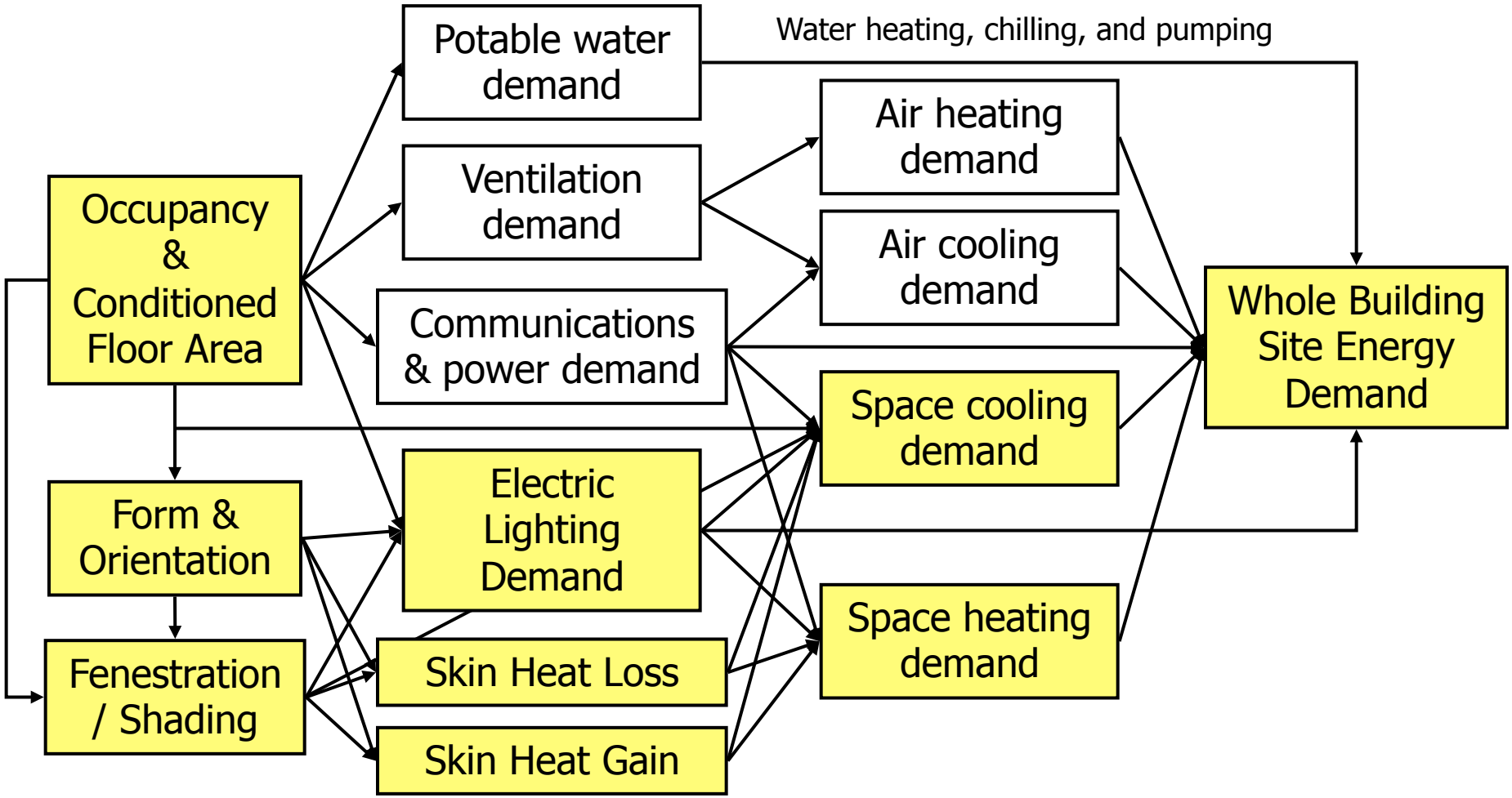
SC3, office of Smith Carter Architects & Engineers, Winnipeg. Photo credit Smith Carter

- Heuristics not measurements:
  - Compact form;
  - Surface Area to Volume ratios;
- Pay attention to variables of façade design:
  - Window area & whole window U-value;
  - Opaque wall area & effective RSI value;
  - Roof area & roof RSI value;
  - Combined envelope areas and Values, or UxA.

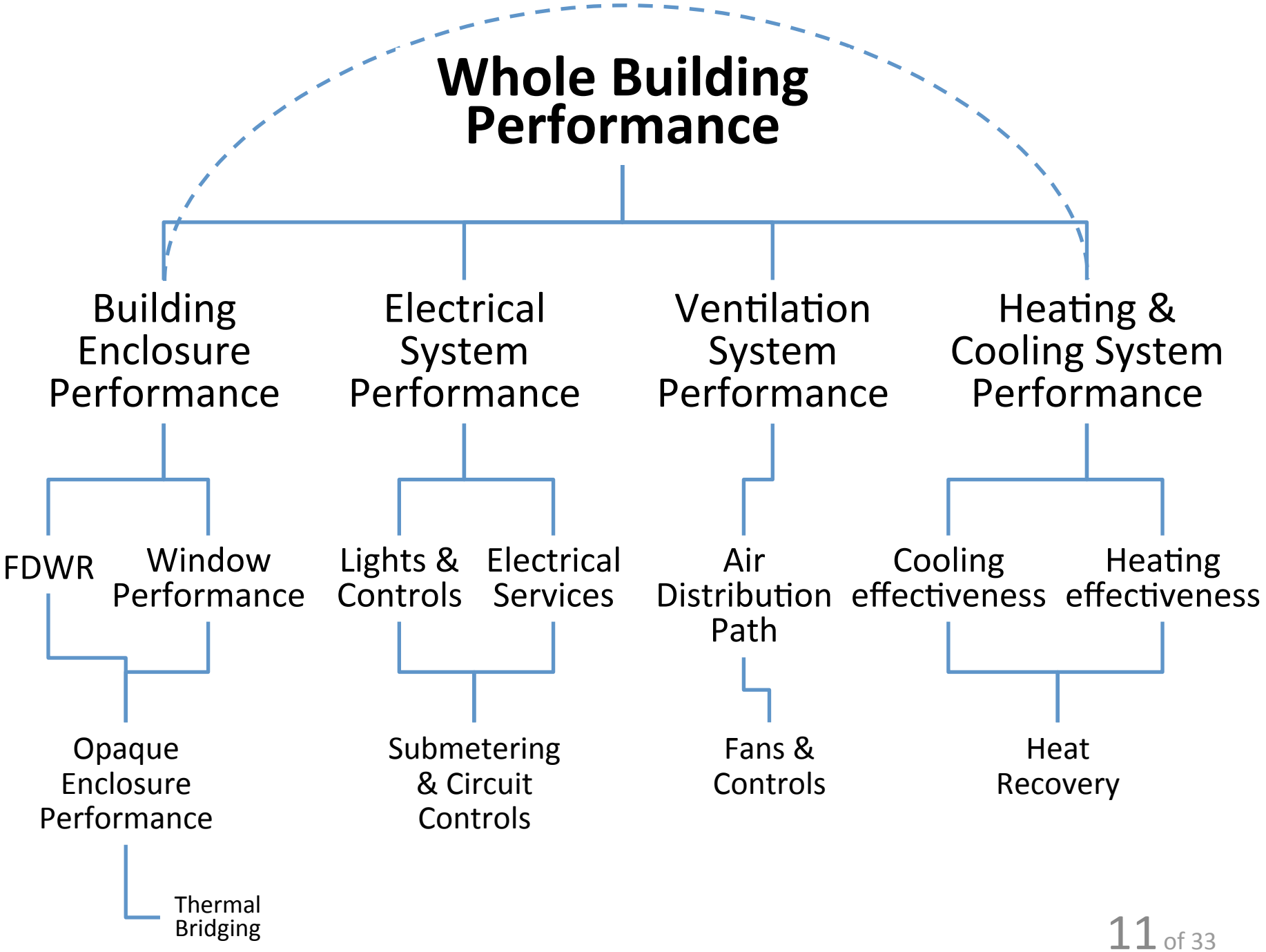
Background Reading:

- Waterloo Architecture M.Arch. Thesis: Barbara Ross
  - Ross, Barbara M. 2009. Design with Energy in Mind, toward a low-load and high-satisfaction civic architecture in the Great Lakes Basin. Master of Architecture thesis. University of Waterloo.
    For details please contact The Research in Architecture Studio, rosstrum@bell.net
  - Chapter 5 contains simulation studies on the impact of form on energy consumption:
    - "The 'types' are designed to probe first into the power of building form. This is necessary, because statements in the literature area at odds with observations made, so far, in this research. …in the search for best practices, building form did not seem to correlate to very low levels of energy intensity. … Contrary to expectations, the least energy-intense cases were more spread out in plan form than compact, and tended to have one plan dimension less than 60 feet." [pg 386]
  - Conclusions offer an excellent summary of the impacts of form and orientation design parameters [pg 441].
- Study on Impact of Surface Area to Volume Ratios on Whole Building Energy Consumption:
  - Caneta Research Inc. for Natural Resources Canada. March 2012;
  - Contact Stephen Pope.

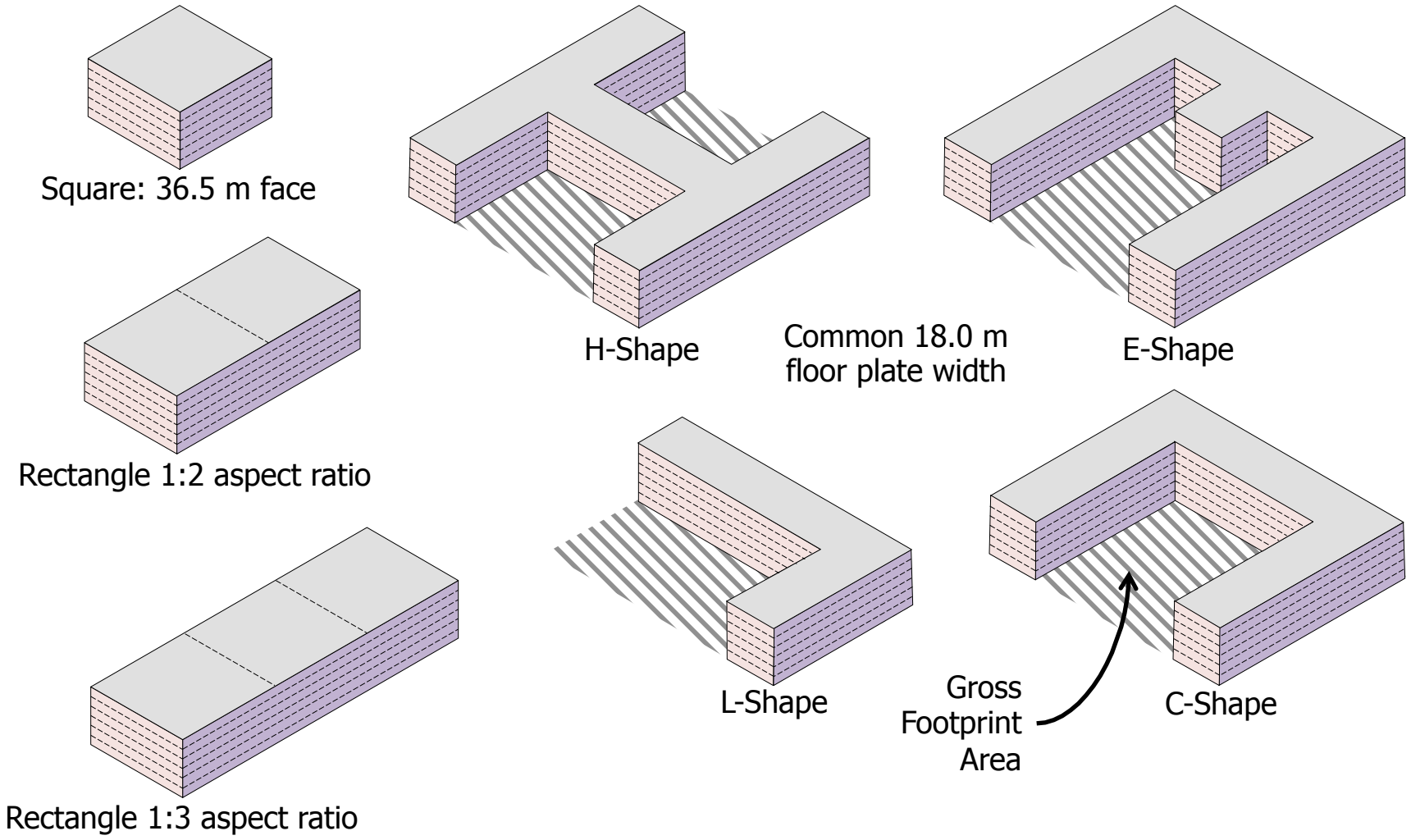
Architecture Sets the Energy Context



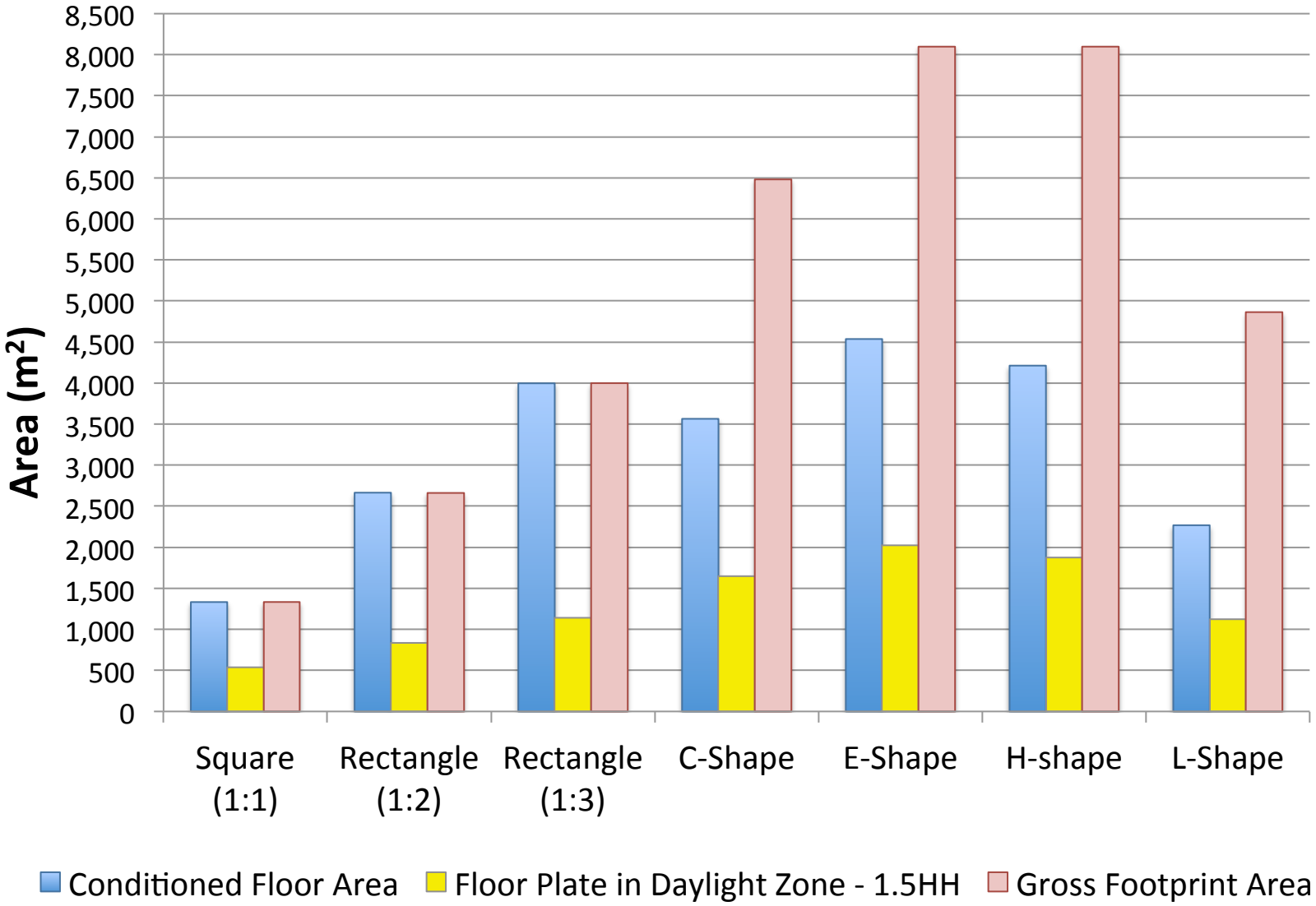
Note: Site climate determines the general magnitude of each end-use.


Whole Building Performance
Building Enclosure Performance
Electrical System Performance
Ventilation System Performance
Heating & Cooling System Performance
FDWR
Window Performance
Lights & Controls
Electrical Services
Air Distribution Path
Cooling effectiveness
Heating effectiveness
Opaque Enclosure Performance
Submetering & Circuit Controls
Fans & Controls
Heat Recovery
Thermal Bridging

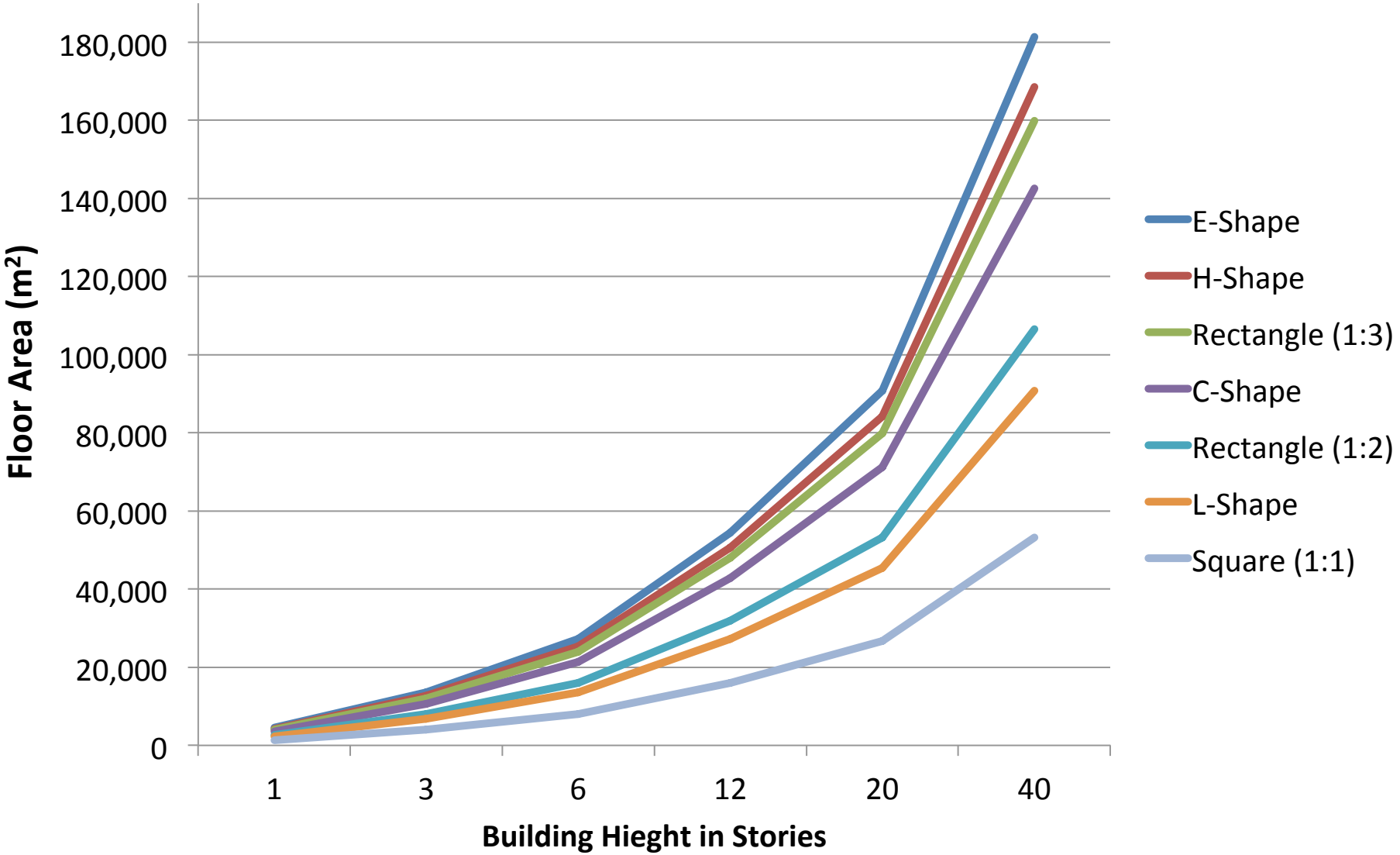
The Study Buildings @ 6 Stories



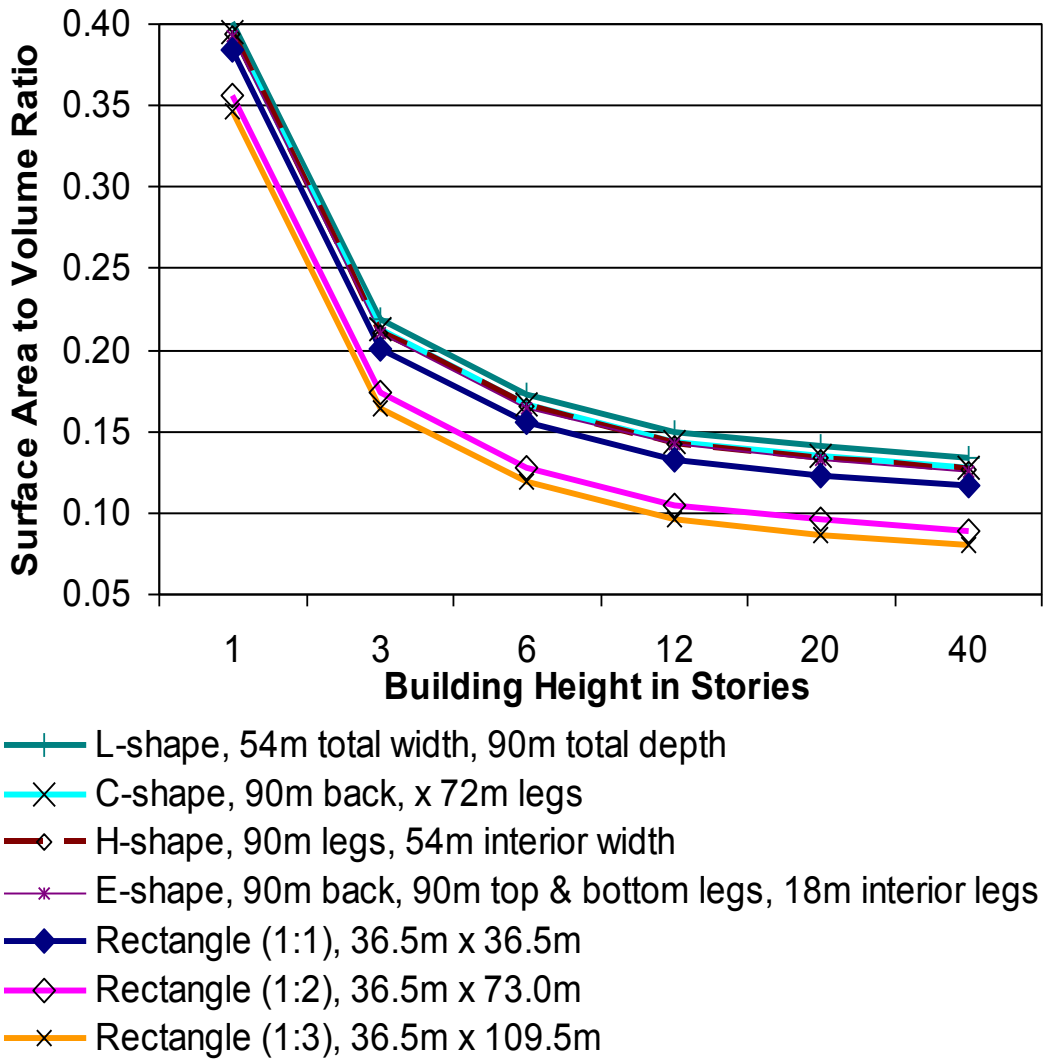
Floor Plate and Daylight Zone



Conditioned Floor Area Comparisons



Surface Area to Volume Ratio Comparison



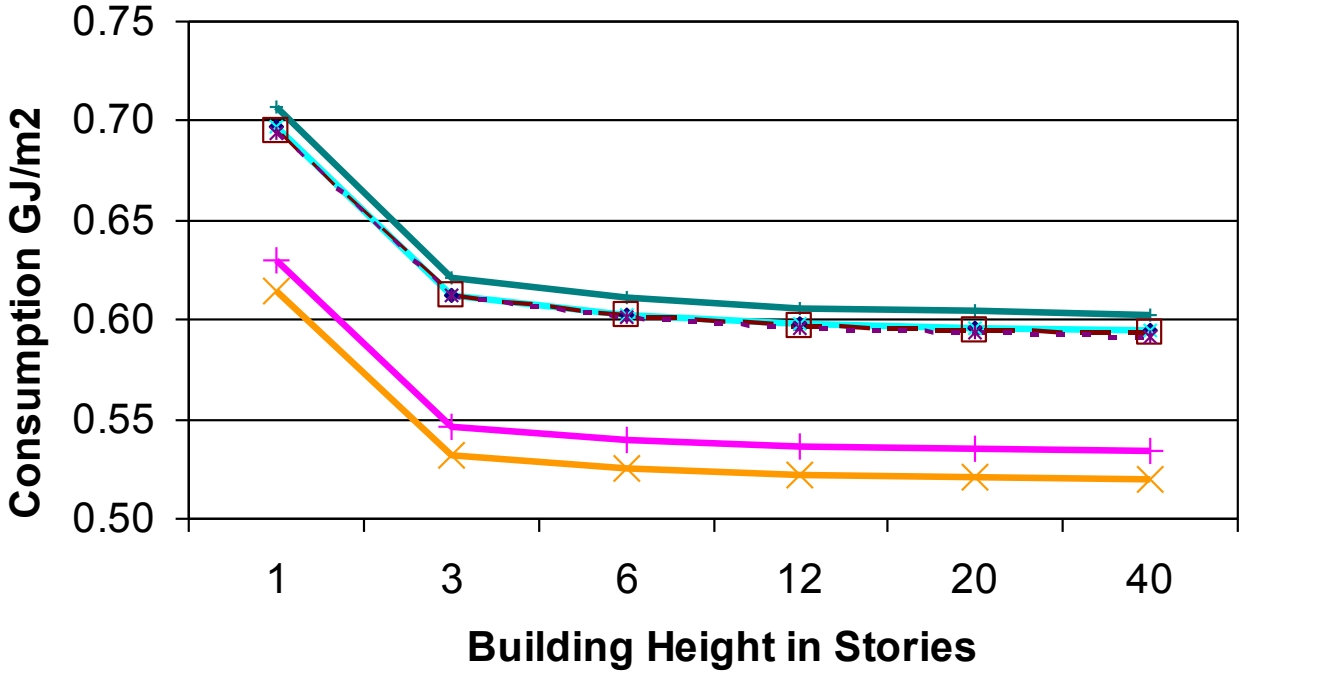
Observations on Geometry

- All shapes have a similar behaviour:
  - Dramatic drop in surface area to volume ratio between 1 and 3 stories;
  - Reductions halve from 3 to 6 stories, and;
  - Diminishing reductions as height increases beyond 6 stories;
- A 12 storey square (closest model to a cube) has:
  - The least ability to house occupants of the 12 storey series, but;
  - Can be deployed on the smallest site;
  - A greater surface area to volume ratio than 1:2, and 1:3 plans;
  - Largest percentage of the floor plate in the daylight control zone of all solid shapes, but;
  - A smaller percentage than all the letter shapes.
- Best performing "thick floorplate" (1:3 rectangle) has:
  - Comparable floor area to letter shapes;
  - Lowest surface area to volume ratio of the whole set.
- Clear distinction between the scale of OBC Part 9 and Part 3;
  - 9 storey concrete frame buildings depend entirely on enclosure values not form;
  - 6 storey "Main Street" buildings are not greatly influenced by form.

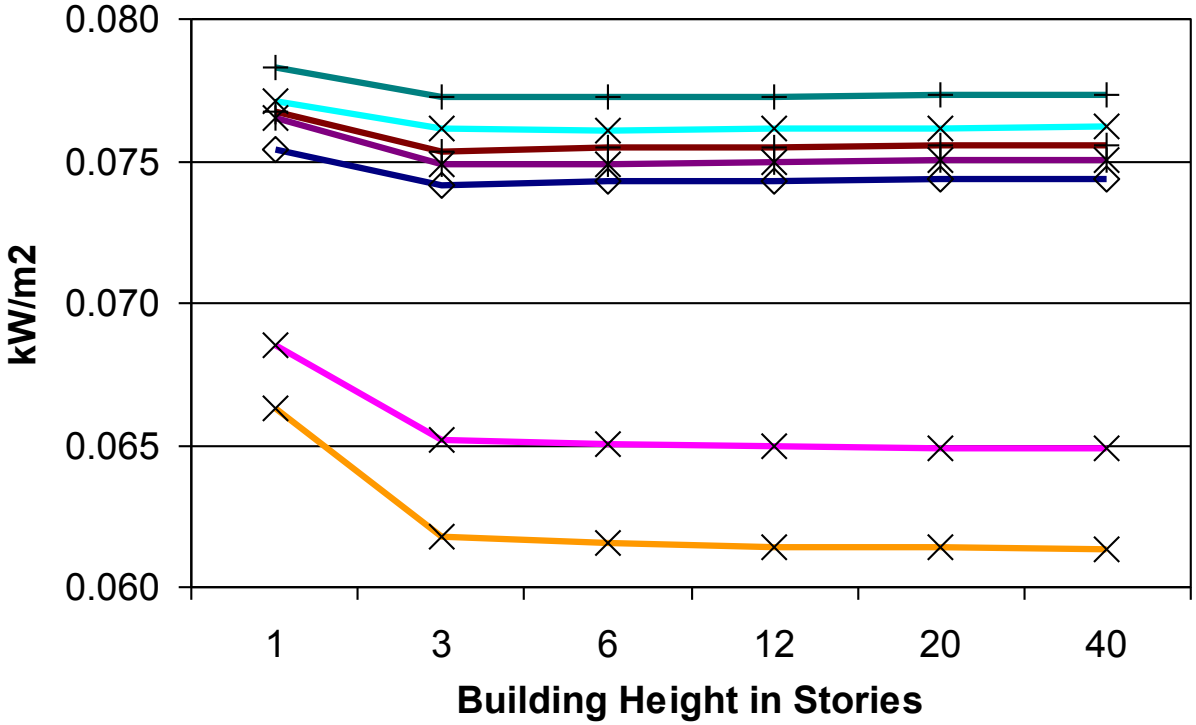
The background details:

- eQuest hourly simulation models using the NECB 2011 reference values:
- 3 storey small office archetype consumes:
  - 654 MJ/m2/yr for NECB 2011 vs.;
  - 968 MJ/m2/yr for MNECB 1997.
- General Inputs (NECB 2011):
  - Central VAV reference HVAC;
  - Occupant density: 25 m2/ person;
  - Roof insulation: RSI 5.5;
  - Wall insulation: RSI 4.0;
- General Inputs continued:
  - FDWR 40%, same all faces;
  - No skylights;
  - Window U-value: 2.2 W/ $m^{2}*^{o}K$;
  - Window SHCG: 0.4;
  - Boiler efficiency: 83%;
  - Chiller COP: 6.1;
  - Electric SHW at 100% efficiency;
  - Connected Lighting Power Density: 9.7 W/m^{2};
  - No daylighting controls;
  - Plug and equipment loads: 7.5 W/m^{2};

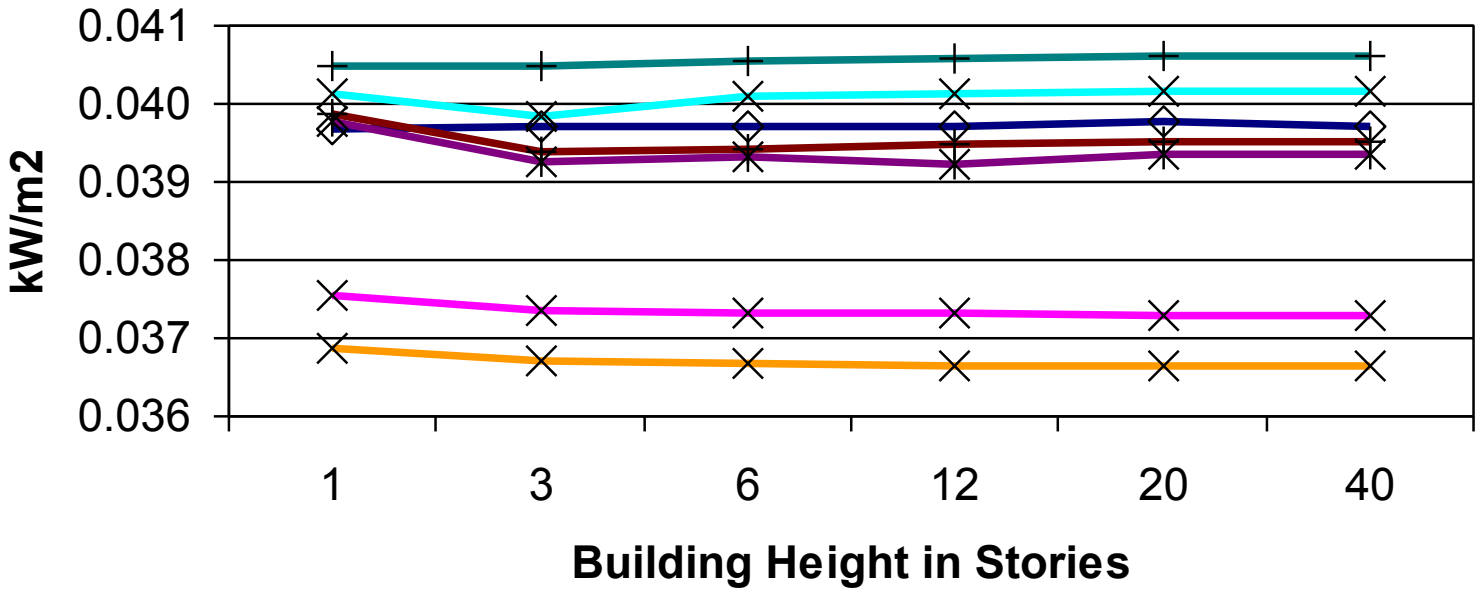
Annual Energy Consumption by Type (Ottawa)



Peak Heating Demand by Bldg Shape (Ottawa)



Peak electricity demand by Bldg Shape (Ottawa)



- L-shape, 54m total width, 90m total depth
- C-shape, 90m back, x 72m legs
- Rectangle (1:1), 36.5m x 36.5m
- H-shape, 90m legs, 54m interior width
- E-shape, 90m back, 90m top & bottom legs, 36m interior legs
- Rectangle (1:2), 36.5m x 73.0m
- Rectangle (1:3), 36.5m x 109.5m

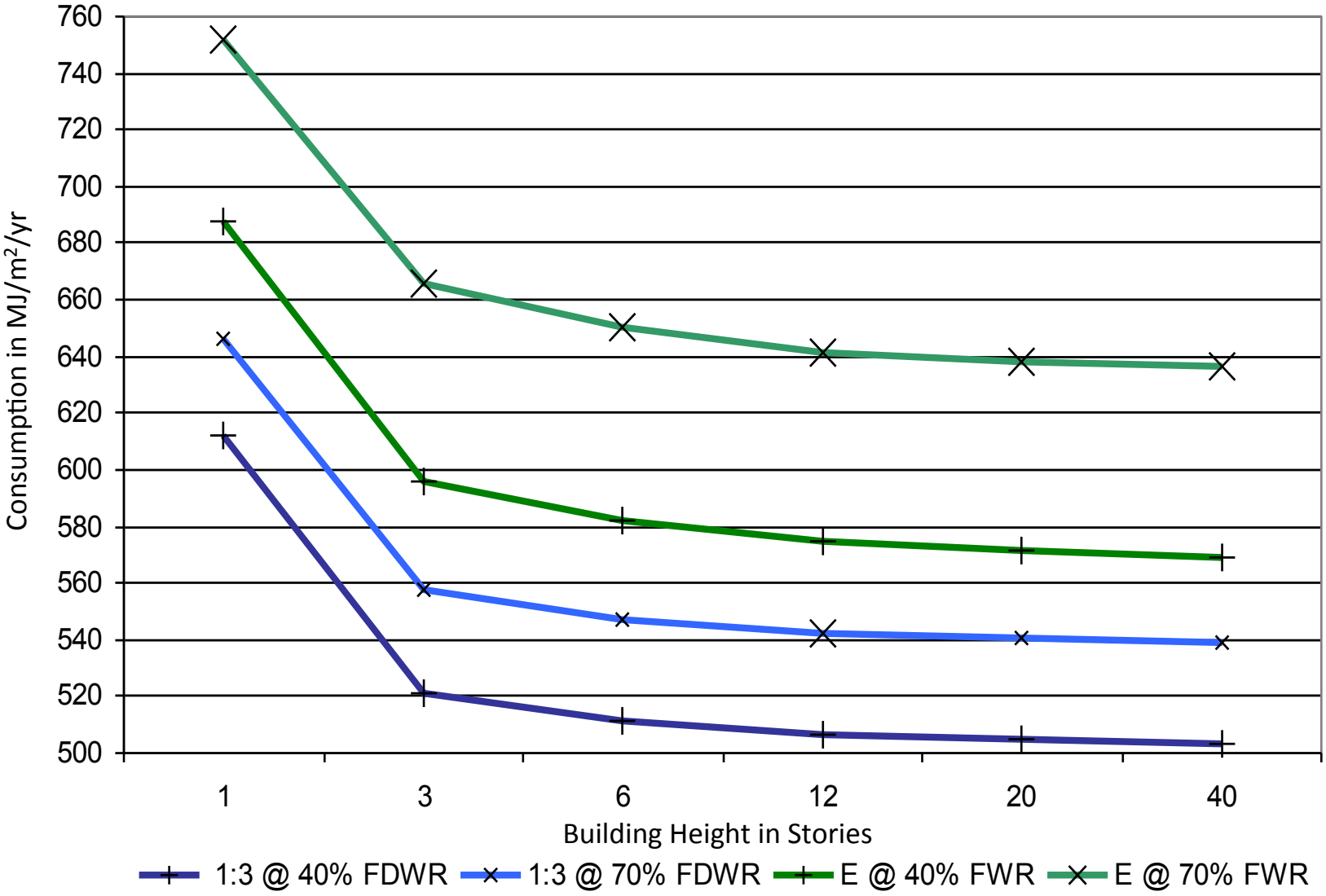
Energy Performance for 12 Storey types

Building Type	Heating Load (GJ/m^2)	Cooling Load (GJ/m^2)	Peak Heating (eW/m^2)	Peak Cooling (W/m^2)
E-Shape	0.23	0.11	75	70
H-Shape	0.22	0.11	75	70
Rectangle (1:3)	0.17	0.11	61	60
C-Shape	0.22	0.11	76	80
Rectangle (1:2)	0.18	0.11	65	60
L-Shape	0.23	0.11	77	80
Square (1:1)	0.21	0.11	74	70

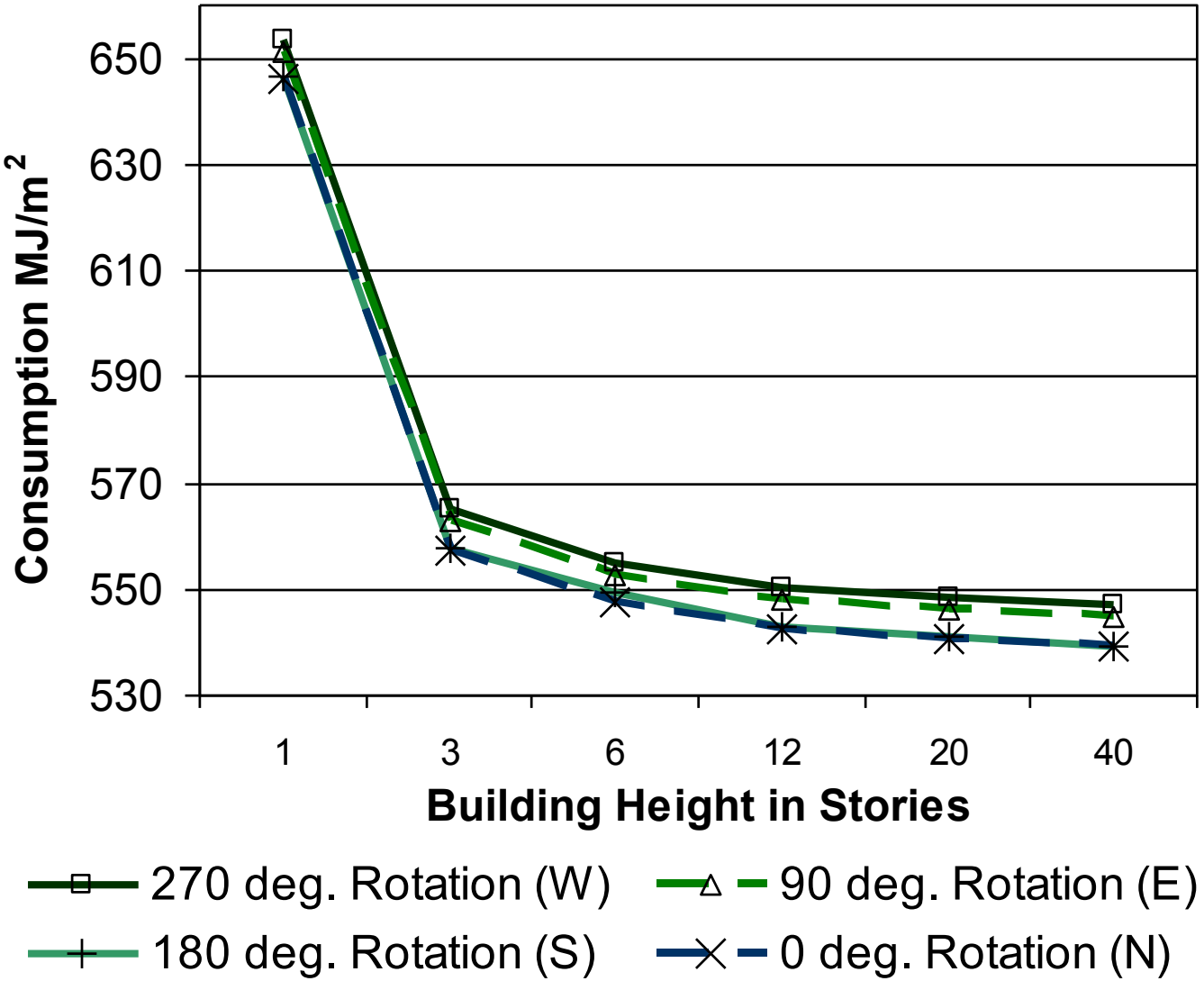
Energy Performance for E-Shape

Building Type	Heating Load (GJ/m^2)	Cooling Load (GJ/m^2)	Peak Heating (eW/m^2)	Peak Cooling (W/m^2)
1 Storey	0.31	0.11	76	70
3 Stories	0.24	0.11	75	70
6 Stories	0.23	0.11	75	70
12 Stories	0.22	0.11	75	70
20 Stories	0.22	0.11	75	70
40 Stories	0.22	0.11	75	70

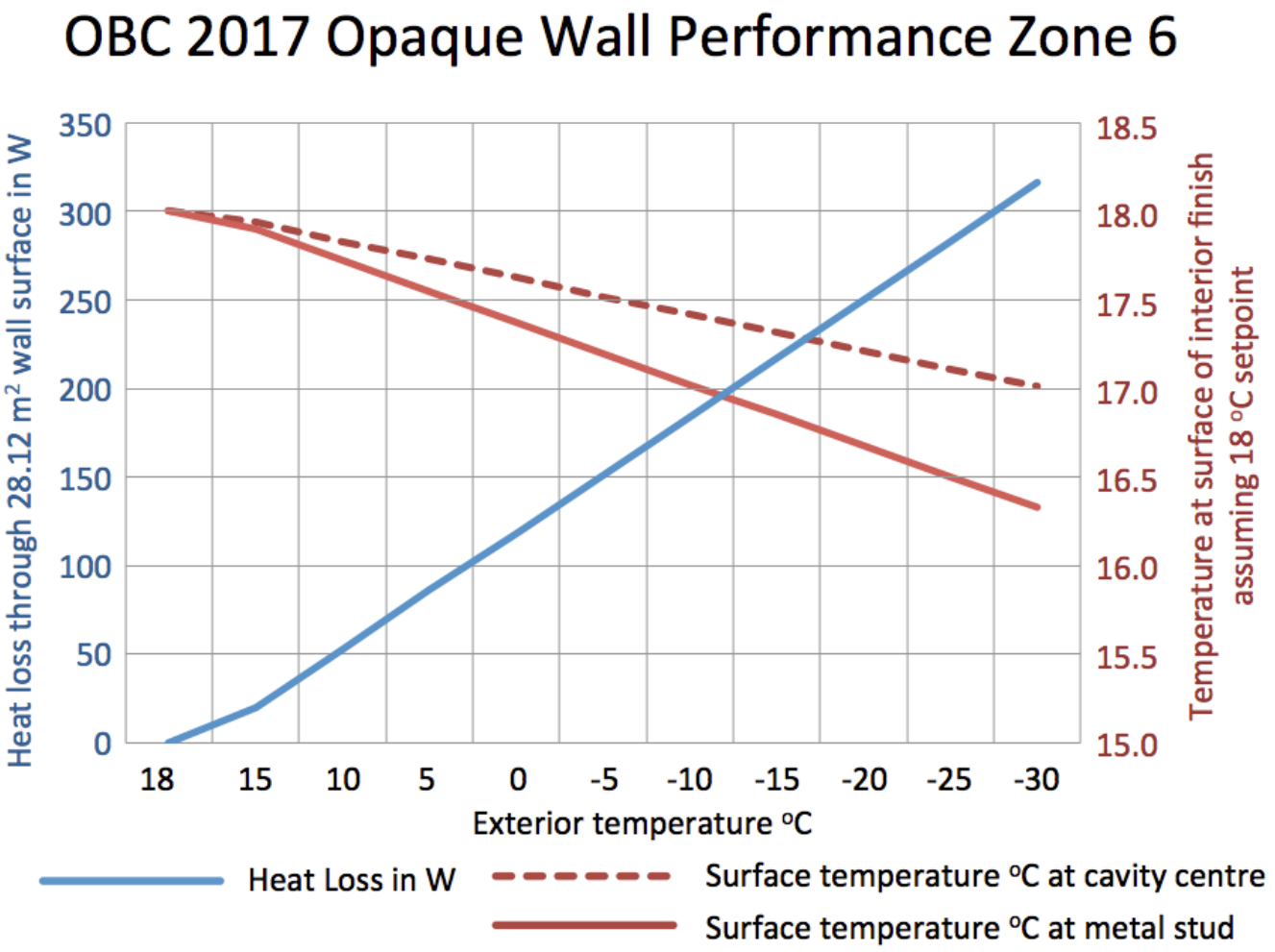
Impact of expanding FDWR



1:3 Rectangular Plan 70% FDWR: rotation impacts



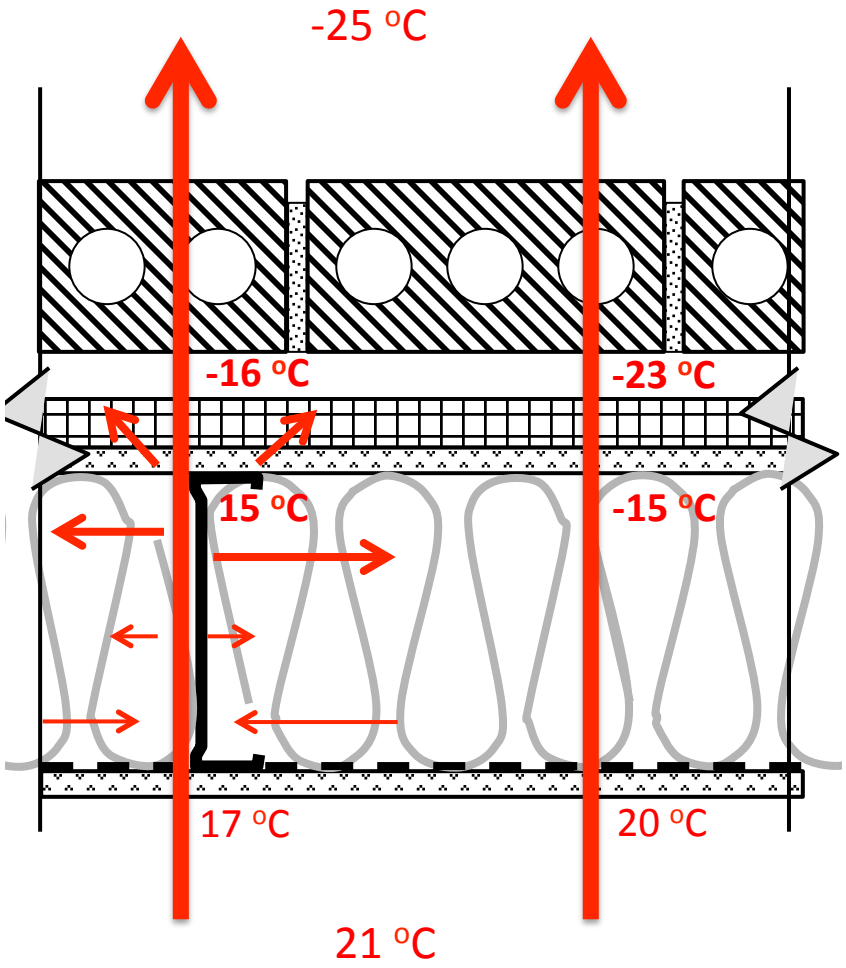
Current Code Performance



Heat Loss Parallel Paths

Path through stud:

- Very small area;
- Heat transmitter not resistor;
- Loses heat to inside of assembly as well as exterior;
- Needs 3D analysis for fine detail.



Path through cavity:

- Very large area;
- Loses heat to exterior in a direct line;
- Can be addressed with 2D analysis.

Conclusions for Surface Area to Volume ratio

- Square may be the “most compact”, but is not the most accommodation or least energy consuming;
- Square plan does not produce significantly different results than letter shaped plans;
- Differences arising from different forms can be mitigated by standard energy efficiency measures;
- **Surface Area to Volume Ratio is not a significant indicator of energy efficiency.**

- Significant energy penalties will not be incurred for increasing skin area for purposes of better access to air, light, or renewable energy. (your mileage may vary)

Balancing Envelope Performance

- A better metric for skin performance;
- U-value x Assembly Area comparisons are the foundation of building / energy code envelope trade-off paths;
- Increased fenestration and door area is compensated by increased wall insulation or lower window U-value;
- Simple trade-offs allow walls to trade with windows or roofs to trade with skylights only.
  - Credit for daylighting requires full performance analysis.

- Only performance analysis allows trade-offs across systems:
  - but trade-off methods are easier than simulation where the envelope is the primary concern.

U x A Calculator (example)

Elements			**Elements**		
1	Gross Roof Area (m^2)		11	Roof UxA ($W/^oC$)	(1-4)*2
2	Roof U-value ($W/^oC*m^2$)		12	Skylight UxA ($W/^oC$)	4*5
3	Percent of Skylights (%)		13	Wall UxA ($W/^oC$)	(6-9)*7
4	Gross Skylight Area (m^2)	1*3	14	Window UxA ($W/^oC$)	9*10
5	Skylight U-value ($W/^oC*m^2$)		15	Building UxA ($W/^oC$)	Σ 11-14
6	Gross Wall Area (m^2)		16	Design dT	
7	Wall U-value ($W/^oC*m^2$)		17	Skin Loss @ Design T (W)	15*16
8	Percent of Windows (%)		18	Simulation Results (GJ/yr)	
9	Gross Window Area (m^2)	6*8			
10	Window U-value ($W/^oC*m^2$)				

- Simple spreadsheet check for preliminary design / massing level detail;
- Start with code defaults for U-values.

Enclosure Performance Balancing @ Design

- Peak heating load based – spreadsheet:
  - Find code references for UxA calculator with proposed project geometry;
  - Identify code minimum UxA;
  - Play with window & wall area, plus window, wall & roof U-values to match or improve upon code performance.
- Energy simulation based (cooling impacts included):
  - Set-up whole building energy simulation for the code reference;
  - Set up performance ranges for different assemblies, and area ranges for different assemblies;
  - Complete batch runs or cloud runs of models and post process results into cloud points or curves;
  - Identify best options under stated conditions.

Balancing tables: square plan “squint overview”

Proportion 1:1:0.01 - 1 storey	Reference																											
UxA @ NECB 2011 Reference Zone 6 (W / °C	740	732	637	O/R[1]	693	725	O/R[1]	O/R[1]	671	O/R[1]	672	716	836	O/R[1]	656	O/R[1]	630	687	O/R[1]	O/R[1]	630	685	684	671	O/R[1]	O/R[1]	6
FDWR	35%	40%	40%	40%	40%	40%	45%	45%	45%	45%	45%	45%	50%	50%	50%	50%	50%	50%	55%	55%	55%	55%	55%	55%	60%	60%	60
[2]Annual Reference Building Consumption (GJ)	945	983	983	983	983	983	1,023	1,023	1,023	1,023	1,023	1,023	1,064	1,064	1,064	1,064	1,064	1,064	1,108	1,108	1,108	1,108	1,108	1,108	1,154	1,154	1,1
Hold Wall & Roof: Change Window U / SC	2.2 / 0.6	2.2 / 0.6	2.2 / 0.6	2.2 / 0.6	2.2 / 0.6	.82 / .56	2.2 / 0.6	.82 / .56	.82 / .56	.82 / .56	.82 / .56	1.55 / 0.5	2.2 / 0.6	1.55 / 0.5	1.55 / 0.5	1.55 / 0.5	1.55 / 0.5	37 / 0.41	2.2 / 0.6	37 / 0.41	37 / 0.41	37 / 0.41	37 / 0.41	23 / 0.41	2.2 / 0.6	1.23 / 0.41	1.23 / 0.
[2]Annual Proposed Building Consumption (GJ)	945	983	945	O/R[1]	945	945	1,023	977	945	O/R[1]	945	945	1064	989	945	O/R[1]	945	945	1,108	957	944	945	945	945	1154	976	9
Hold Wall & Window: Change Roof RSI	5.46	5.46	8.9	5.46	7.5	5.15	5.46	5.46	8.2	5.46	7.5	4.9	5.46	5.46	7.5	5.46	6.5	5.3	5.46	5.46	6.3	5.46	5.6	5.3	5.46	5.46	8
Hold Roof & Window: Change Wall RSI	4.06	4.06	4.06	O/R[1]	6	4.06	4.06	4.06	4.06	O/R[1]	5	4.06	4.06	4.06	4.06	O/R[1]	6.2	4.06	4.06	4.06	4.06	6.1	5.5	4.06	4.06	4.06	4.0
	95% Ref																											
	35% FWR	40% FWR					45% FWR						50% FWR						55% FWR						60			
	1	2	3	4	5	6	7	8	9	10					15					20				25				

Proportion 1:1:0.03 - 3 Storey	Reference																											
UxA @ NECB 2011 Reference Zone 6 (W / °C	1,731	O/R[1]	O/R[1]	O/R[1]	1,631	1,645	1,687	1,686	1,683	O/R[1]	1644	1643	1643	O/R[1]	O/R[1]	O/R[1]	O/R[1]	1,510	1683	O/R[1]	O/R[1]	1,543	1571	O/R[1]	O/R[1]	O/R[1]	O/R[1]
FDWR	35%	40%	40%	40%	40%	40%	40%	40%	40%	45%	45%	45%	45%	50%	50%	50%	50%	50%	50%	55%	55%	55%	55%	60%	60%	60%	60
[2]Annual Reference Building Consumption (GJ)	2,655	2,755	2,755	2,755	2,755	2,755	2,755	2,755	2,755	2,860	2,860	2,860	2,860	2,370	2,370	2,370	2,370	2,370	2,370	3,086	3,086	3,086	3,086	3,207	3,207	3,207	3,2
Hold Wall & Roof: Change Window U / SC	2.2 / 0.6	2.2 / 0.6	2.2 / 0.6	2.2 / 0.6	2.2 / 0.6	.82 / .56	.82 / .56	.82 / .56	.82 / .56	2.2 / 0.6	1.55 / .5	1.55 / .5	1.55 / .5	2.2 / 0.6	1.55 / .5	1.55 / .5	1.55 / .5	1.55 / .5	37 / .41	2.2 / 0.6	1.37 / .41	1.37 / .41	1.37 / .41	2.2 / 0.6	1.37 / .41	1.37 / .41	1.37 / .
[2]Annual Reference Building Consumption (GJ)	2,655	2,755	2,693	2,684	2,655	2,640	2,655	2,655	2,654	2,860	2,653	2,654	2,653	2,370	2,723	2,658	2,660	2,654	2,654	3,086	2,683	2,653	2,653	3,207	2,773	2,709	2,7
Hold Wall & Window: Change Roof U	5.46	5.46	15	5.46	10	5.46	4.65	5.46	5.00	5.46	4.8	4.2	5.46	5.46	5.46	17.00	5.46	3	3.7	5.46	5.46	8.00	5.46	5.46	5.46	15	5.4
Hold Roof & Window: Change Wall U	4.06	4.06	4.06	15	10	4.06	4.06	3.45	3.8	4.06	3.5	4.06	3.1	4.06	4.06	4.06	15	6.5	3.5	4.06	4.06	4.06	5.3	4.06	4.06	4.06	
	95% Ref																										
	35% FWR	40% FWR							45% FWR					50% FWR						55% FWR					60% FWR		

Proportion 1:1:0.06 - 6 storey	Reference																											
UxA @ NECB 2011 Reference Zone 6 (W / °C	3,219	O/R[1]	O/R[1]	O/R[1]	3,032	3,247	O/R[1]	O/R[1]	O/R[1]	O/R[1]	2,865	3,050	O/R[1]	O/R[1]	O/R[1]	O/R[1]	2,793	3331	O/R[1]	O/R[1]	2,873	2,305	2833	O/R[1]	O/R[1]	O/R[1]	O/R[1]
FDWR	35%	40%	40%	40%	40%	40%	45%	45%	45%	45%	45%	45%	50%	50%	50%	50%	50%	50%	55%	55%	55%	55%	55%	60%	60%	60%	60
[2]Annual Reference Building Consumption (GJ)	5218	5412	5412	5412	5412	5412	5,615	5,615	5,615	5,615	5,615	5,615	5,829	5,829	5,829	5,829	5,829	5,829	6,052	6,052	6,052	6,052	6,052	6,286	6,286	6,286	6,28
Hold Wall & Roof: Change Window U / SC	2.2 / .6	2.2 / .6	2.2 / .6	2.2 / .6	2.2 / .6	.82 / .56	2.2 / .6	.82 / .56	.82 / .56	.82 / .56	.82 / .56	1.55 / .5	2.2 / .6	1.55 / .5	1.55 / .5	1.55 / .5	1.55 / .5	1.37 / .41	2.2 / 0.6	37 / 0.41	37 / 0.41	37 / 0.41	37 / 0.41	2.2 / 0.6	1.37 / 0.4	1.37 / 0.4	1.37 / 0
[2]Annual Reference Building Consumption (GJ)	5,218	5,412	5,350	5,276	5,217	5,216	5,615	5,384	5,323	5,260	5,218	5,218	5,823	5,350	5,289	5,228	5,218	5,217	6,052	5,271	5,218	5,218	5,217	6,286	5,445	5,381	5,30
Hold Wall & Window: Change Roof U	5.46	5.46	15	5.46	15	5.5	5.46	5.46	15	5.46	14.5	4.2	5.46	5.46	15	5.46	9.00	3.50	5.46	5.46	12.30	5.46	5.80	5.46	5.46	15	5.4
Hold Roof & Window: Change Wall U	4.06	4.06	4.06	15	15	3.5	4.06	4.06	4.06	15	11.4	3.5	4.06	4.06	4.06	15	9.70	3.00	4.06	4.06	4.06	5.70	5.50	4.06	4.06	4.06	
	Reference																										
	35%	40% FWR					45% FWR						50% FWR						55% FWR					60% FWR			

Proportion 1:1:1.2 - 12 storey	Reference																											
UxA @ NECB 2011 Reference Zone 6 (W / °C	6,819	O/R[1]	6,700	6,405	6,522	O/R[1]	O/R[1]	O/R[1]	6,308	O/R[1]	6,163	O/R[1]	O/R[1]	O/R[1]	6,319	6,456	5,872	O/R[1]	O/R[1]	O/R[1]	5,977	6,090	O/R[1]	O/R[1]	O/R[1]	O/R[1]	5,7
FDWR	35%	40%	40%	40%	40%	45%	45%	45%	45%	45%	45%	45%	50%	50%	50%	50%	50%	50%	55%	55%	55%	55%	55%	60%	60%	60%	60
[2]Annual Reference Building Consumption (GJ)	9,780	10,106	10,106	10,106	10,106	10,445	10,445	10,445	10,445	10,445	10,445	10,737	10,737	10,737	10,737	10,737	10,737	11,164	11,164	11,164	11,164	11,164	11,164	11,545	11,545	11,545	11,5
Hold Wall & Roof: Change Window U / SC	2.2 / .6	2.2 / .6	2.2 / .6	2.2 / .6	2.2 / .6	2.2 / .6	2.2 / .6	2.2 / .6	2.2 / .6	.82 / .56	.82 / .56	2.2 / 0.6	.82 / .56	.82 / .56	.82 / .56	.82 / .56	1.55 / .5	2.2 / 0.6	1.55 / .5	1.55 / .5	1.55 / .5	1.55 / .5	37 / 0.41	2.2 / 0.6	1.37 / 0.41	1.37 / 0.41	1.37 / 0.
[2]Annual Reference Building Consumption (GJ)	9,780	10,106	9,779	9,776	9780	10,445	9,396	9,861	9,779	9,373	9,778	10,737	10,300	9,853	9,777	9,777	9,780	11,164	10,243	9,806	9,779	9,775	9,929	11,545	10,246	9,810	9,7
Hold Wall & Window: Change Roof U	5.46	5.46	10.7	5.46	6.8	5.46	15	5.46	9	5.46	6	5.46	5.46	15	5.46	8	6	5.46	5.64	15	5.46	8	5.46	5.46	5.46	15	5.4
Hold Roof & Window: Change Wall U	4.06	4.06	4.06	7.2	5.5	4.06	4.06	15	8.2	4.06	5	4.06	4.06	4.06	12.5	6.8	4.6	4.06	4.06	4.06	10.2	6.1	4.06	4.06	4.06	4.06	
	Reference																										
	35%	40% FWR					45% FWR						50% FWR						55% FWR					60% FWR			

Proportion 1:1:2 - 20 Storey	Reference																											
UxA @ NECB 2011 Reference Zone 6 (W / °C	6,819	O/R[1]	O/R[1]	10525	10565	7759	O/R[1]	O/R[1]	10307	10040	9388	O/R[1]	O/R[1]	9733	8260	9091	O/R[1]	O/R[1]	9125	9215	8647	O/R[1]	O/R[1]	O/R[1]	8685	8827	836
FDWR	35%	40%	40%	40%	40%	40%	45%	45%	45%	45%	45%	50%	50%	50%	50%	50%	55%	55%	55%	55%	55%	60%	60%	60%	60%	60%	60
[2]Annual Reference Building Consumption (GJ)	15,879	16,398	16,398	16,398	16,398	16,398	16,398	16,184	16,184	16,184	16,184	17,499	17,499	17,499	17,499	17,499	18,083	18,083	18,083	18,083	18,083	18,690	18,690	18,690	18,690	18,690	18,63
Hold Wall & Roof: Change Window U / SC	2.2 / .6	2.2 / .6	2.2 / .6	2.2 / .6	2.2 / .6	.82 / .56	2.2 / 0.6	.82 / .56	.82 / .56	.82 / .56	1.55 / 0.5	2.2 / 0.6	1.55 / 0.5	1.55 / 0.5	1.55 / 0.5	1.37 / .41	2.2 / 0.6	1.37 / .41	1.37 / .41	1.37 / .41	1.23 / .41	2.2 / 0.6	1.23 / .41	1.23 / .41	1.23 / .41	1.23 / .41	1.12 / .
[2]Annual Reference Building Consumption (GJ)	15,879	16,398	15973	15879	15859	15869	16,398	16184	15879	15877	15878	17499	16017	15875	15866	15866	18083	16114	15876	15870	15877	18690	16348	15924	15800	15874	158
Hold Wall & Window: Change Roof U	5.46	5.46	15	5.46	7.5	5.4	5.46	5.46	10.2	5.46	4.8	5.46	5.46	8.5	5.46	5	5.46	5.46	8.6	5.46	5.3	5.46	5.46	15	5.46	7.2	5
Hold Roof & Window: Change Wall U	4.06	4.06	4.06	7.1	5.8	3.5	4.06	4.06	4.06	5.5	3.5	4.06	4.06	4.06	5.1	3.5	4.06	4.06	4.06	5.1	4.06	4.06	4.06	4.06	7.4	5.5	4

Balancing: Results @ 1:1:0.3 (3 Storey)

Proportion 1:1:0.3	Ref.	40% FDWR	45% FDWR	50% FDWR	55% FDWR	60% FDWR	65% FDWR	70% FDWR
UxA (W/^{o}K)	1,731	1,683	1,644	1,683	1,571	1,444	1,451	1,348
FDWR	35%	40%	45%	50%	55%	60%	65%	70%
Annual Ref. Bldg Cons. (GJ)	2,655	2,755	2,860	2,970	3,086	3,207	3,334	3,467
Window U	2.2	1.82	1.55	1.37	1.37	1.12	1.12	0.94
Window SC	0.6	0.56	0.5	0.41	0.41	0.31	0.31	0.25
Annual Building Cons. (GJ)	2,655	2,654	2,653	2,654	2,653	2,652	2,655	2,655
Roof RSI	5.46	5.00	4.8	3.7	5.46	5.46	7.5	6.5
Wall RSI	4.06	3.8	3.5	3.5	5.9	5.3	5.1	5.3

- Proportion 1:1:0.3 (3 storey, square plan) had successful examples up to 70% FDWR;
- Process: Set FDWR; Set glass performance; find UxA<Reference by changing roof insulation; find UxA<Reference by changing wall or roof insulation from reference level; find “best balance” UxA<Reference; check annual consumption < Reference.

Concluding Observations

- Need to develop new “rules of thumb” that correctly guide designers;
- Building form is not a good proxy for energy efficiency;
- Scale matters: form is much more important for OBC Part 9 than it is for OBC Part 3;
- Regardless of where form can be meaningful enclosure performance can counterbalance any negative effects;
- A wide range in FDWR is available if the purchase of IGUs with triple glazing and good low-e coatings are available;