ADAPTING PASSIVE HOUSE TO TORONTO'S EXISTING HOUSING STOCK THROUGH DEEP ENERGY RETROFITS

Vithusan Vimal, Russell Richman
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Ryerson University

URBAN EQUATION

VITHUSAN VIMAL

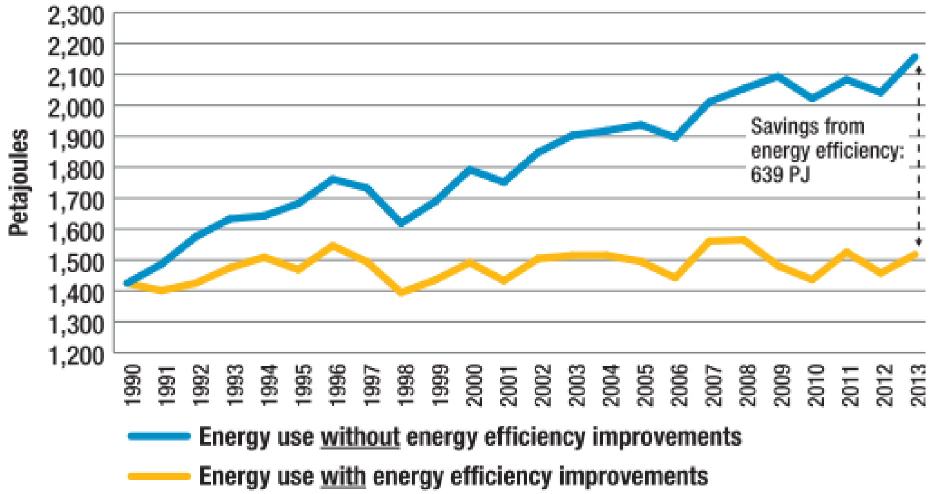
BA, MBSc, CPHC

Vithusan.vimal@Ryerson.ca | (647)-382-7914

Vithusan Vimal is a Master's of Building Science graduate from Ryerson University with an undergraduate degree in architecture from the University of Toronto. He has been consulting and researching in the field of building science for many years and is adamant on developing strategies which makes sustainable buildings a priority for cities. In his research paper he developed deep energy retrofits at low life cycle costs which allows existing homes in downtown Toronto to achieve Passive House certification.

INTRODUCTION

- 30% of energy used in Canada is from buildings (NRCan, 2005)
- 40% increase in residential buildings from 1990-2013 led to 6.5% increase in energy used (NRCan, 2016)
- 2013 Efficiency standards improved energy use by 45% leading to reduction of 27 megatonnes of greenhouse gas emissions (NRCan, 2016)



(NRCan, 2016)

- Still buildings in Toronto accounted for 17% of secondary energy use and 14% of greenhouse gas emissions (NRCan, 2014)

INTRODUCTION

- City of Toronto's ZEB framework: policies for **new buildings** to meet higher performance standards
  - No standards for **existing buildings**
- Retrofitting is the best solution to achieving sustainability in the built environment
- Retrofitting existing structures with new efficient standards is the most cost effective and long-lasting opportunity to decrease energy use and greenhouse gas emissions (Center for Energy, 2013)
- Need to model existing homes to develop retrofit strategies to reduce energy use
- In Toronto there are many single family homes on tight narrow niches with minimal amount of room for redevelopment
  - Single family homes have the highest energy usage

BACKGROUND

- In Toronto 23 urban neighbourhoods were sampled to develop archetype models
- 35% were single family with the main housing types century detached, 70’s OBC, wartime, and modern
- Existing homes are poorly functioning (Jermyn, 2014)

Century Home

Wartime Bungalow

1970’s OBC Home

Modern Home

(Blaszak & Richman, 2013)

Learning Objectives

1) Demonstrate the applicability of high performance building retrofits and standards to an existing housing stock
2) Impact of creating representative models in BEopt, EnergyPlus, and WUFI Passive
3) Methodology to achieving a low life cycle cost retrofit for existing homes
4) Achieving Passive House certification for existing homes is feasible
5) Benefit of using computer modelling tools through all phases of a design

RESEARCH OBJECTIVE

- What cost effective combination of high performance design variables are necessary to meet PHIUS Standards
- Create an multi-objective optimization environment to test energy use and life cycle cost
- Retrofit strategies are analyzed on archetype models that define Toronto's housing stock
- Analyze the cost to energy efficiency trade-offs to extrapolate the data to the housing stock in Toronto

RESEARCH QUESTION

1. Using three archetypes representing a high percentage of Toronto's single family housing, what low-cost combination of energy conservation measures can be utilized to achieve a minimum level of Passive House certification?

LITERATURE REVIEW - Top-Down vs. Bottom-Up Modelling

Top-down: Relationship of energy use to factors such as:

- Population growth, fuel prices, climate conditions, and gross domestic products

- Used to indicate the relationship of economic factors to energy use
- Use historical data and not specific to building type

Bottom-up: Uses a smaller subset of houses to develop an archetype to represent a larger housing stock

- Calculate energy use using relationships with building components

LITERATURE REVIEW - BOTTOM-UP MODELLING

- Main types: statistical bottom-up models or **physics based bottom-up models**
  - Statistical uses historical data vs. physics based uses energy modelling software
- Limitations:
  - Few models to represent a larger housing stock
  - Built on surveys and field studies
  - Based on assumptions and simplifications

LITERATURE REVIEW - TORONTO ARCHETYPE PROJECT

2010

Blaszak and Richman
developed 4 archetypes to represent Toronto housing and utilized retrofits to meet 100 kWh/m²

2013

Mucciarone
developed high performance wall assemblies for a century home in Toronto

Zirnhelt and Richman
produced a methodology to calibrate energy models for single family homes

2014

Jermyn
performed brute force optimization on century and wartime homes to meet 75 kWh/m²

2016

Tokarik
analyzed passive conservation measures to reduce energy use by 33%

Niger
performed brute force optimization on 1970's OBC homes to meet 75 kWh/m²

2020

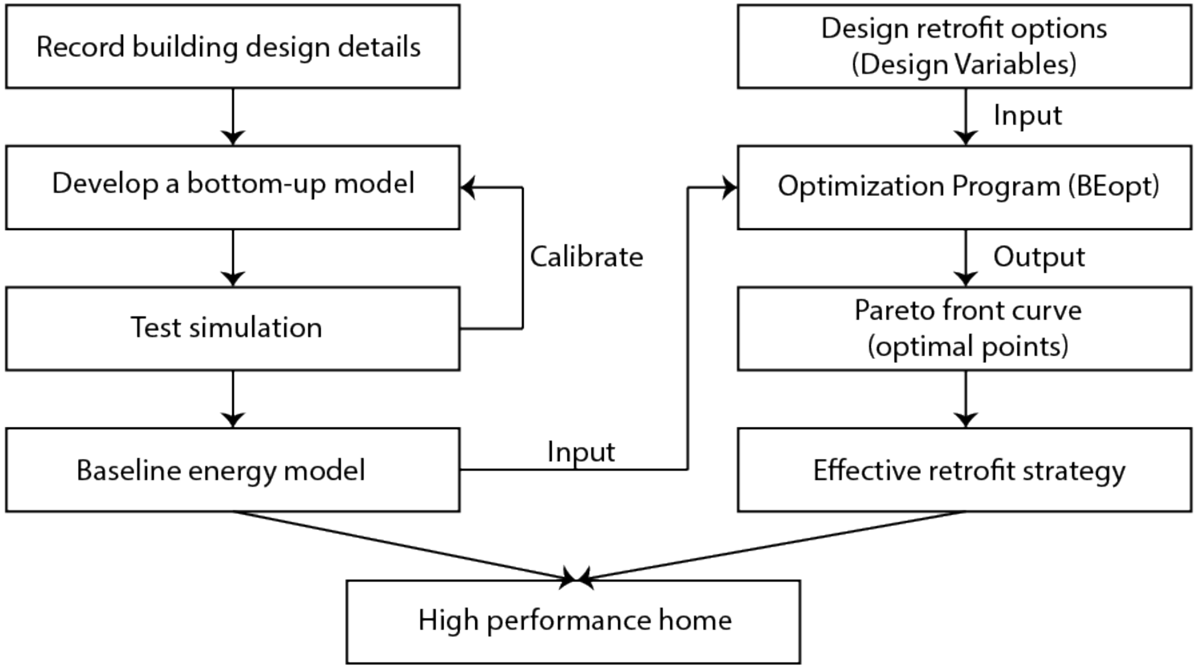
Lawrence and Skarupa
performed surrogate modelling to predict energy use of century attached and detached homes

2021

Vimal
developed retrofit stratgies to allow century and wartime homes to meet Passive House certification

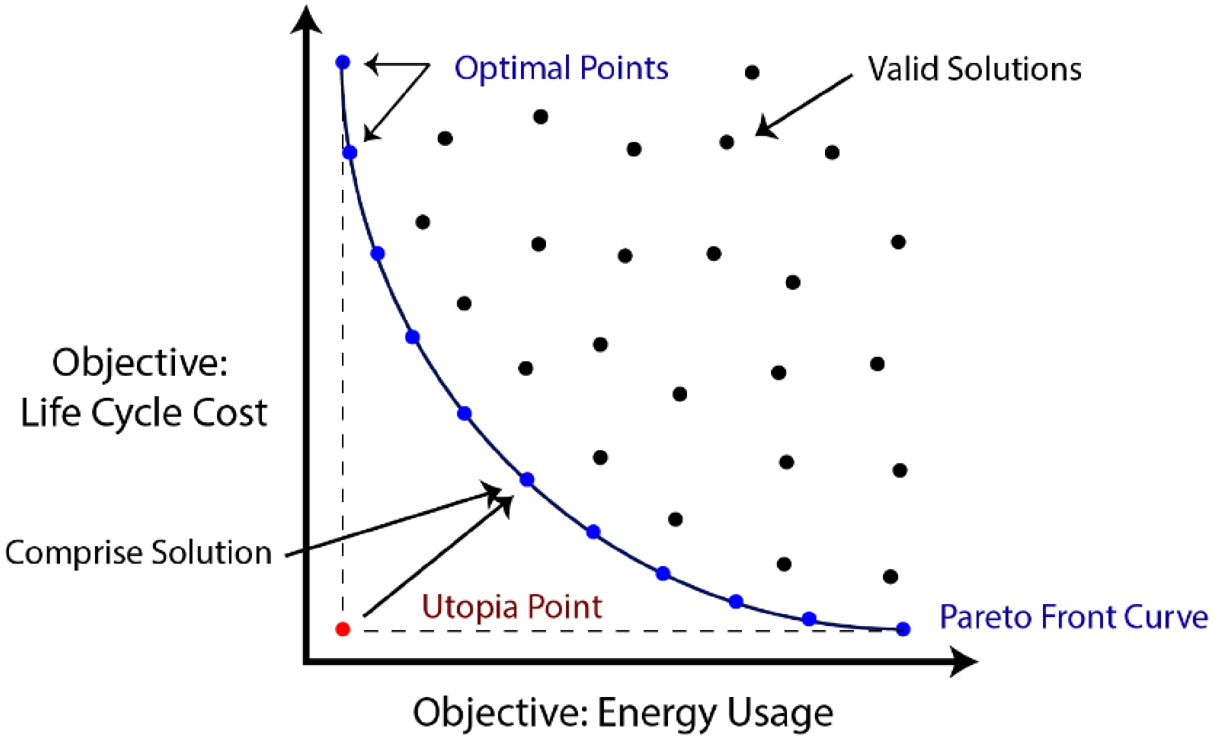
LITERATURE REVIEW – SIMULATION-BASED OPTIMIZATION

- Most effective method to develop low-cost and efficient building constructions
- A whole building or whole systems approach must be used
  - Interaction between various components in a larger system will develop accurate cost effective solutions



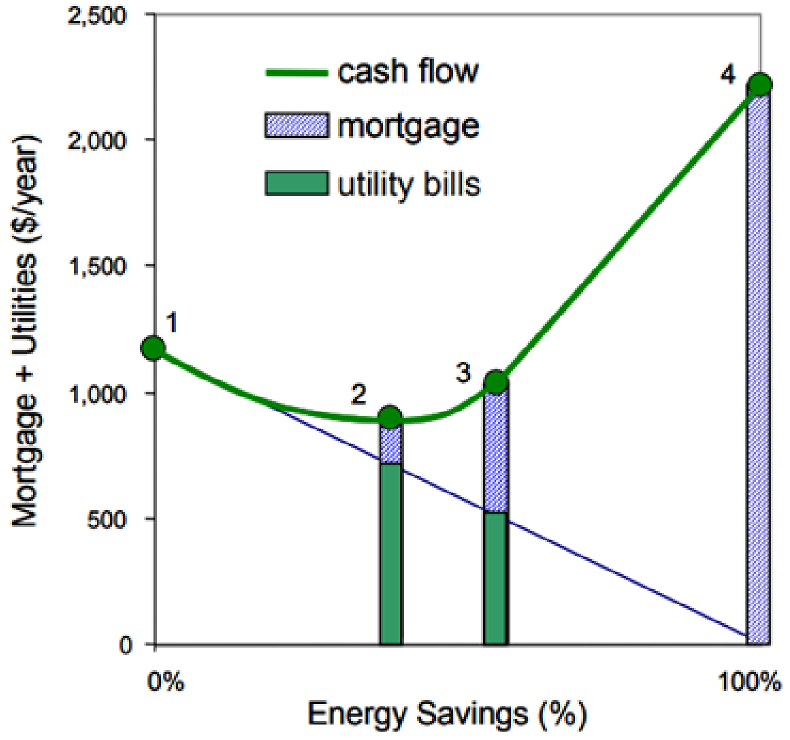
LITERATURE REVIEW – MULTI-OBJECTIVE OPTIMIZATION

- Multi-objective optimization uses a **limited** amount of design variables and typically **two** objective functions



LITERATURE REVIEW – OPTIMIZATION OUTPUT

- Conceptual output graph for a multi-objective optimization:



(G. Wright , K. Klingenberg, 2015)

LITERATURE REVIEW – PASSIVE HOUSE AS A SOLUTION

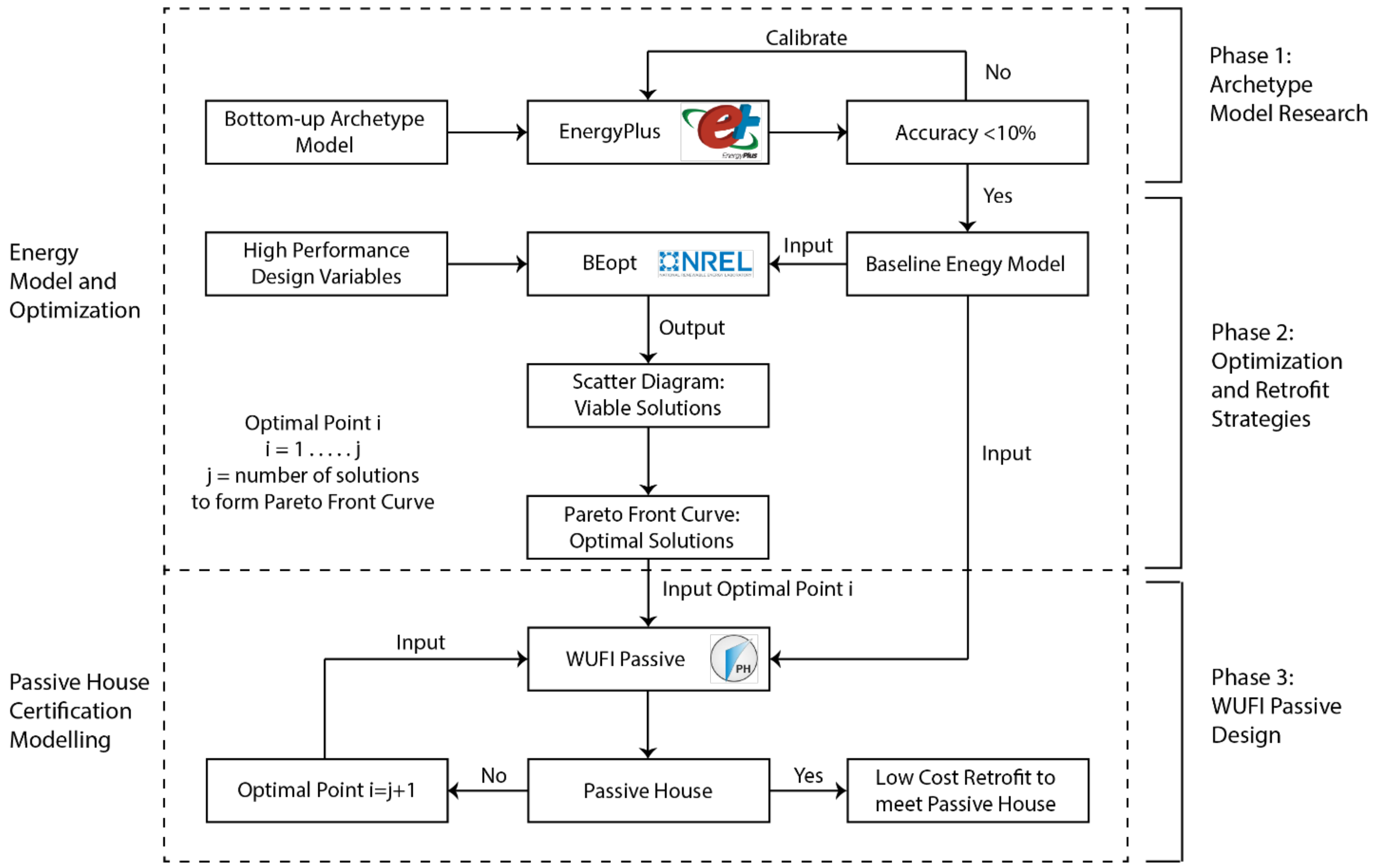
- Certification requires structures to meet climate specific building standards
  - Passive conservation measures
  - Minimum Ventilation Rates
- Structures will have:
  - Improved **thermal comfort**
  - Higher **structural durability** (moisture mitigation)
  - Increased **resilience** (less heat losses to environment)
- Achieving passive house could be a feasible solution to solving comfort and thermal issues
- Recognized by Toronto ZEB framework as a path to achieve its highest tier of requirements

LITERATURE REVIEW – GAPS IN LITERATURE

- Lack of calibration of energy models for a multi-objective optimization
- Overgeneralization of the housing stock
- Retrofit strategies were developed to meet low energy targets instead of high performance targets
- Multiple studies investigate only a singular objective function

(PHIUS,2021)

METHODOLOGY



METHODOLOGY – PHASE 1: ARCHETYPE MODEL DEVELOPMENT

- Toronto neighbourhood profiles report was utilized by Blaszak to determine the four housing types
- 5 most energy intensive neighbourhoods were identified to categorize the EUI percentage by archetype

	# of Single-Detached Dwellings by Archetype				Overall Energy Intensity by Archetype (%)			
Name	**Century**	**Wartime**	**70s OBC**	**Modern**	**Century**	**Wartime**	**70s OBC**	**Modern**
North Riverdale	573	80	30	5	88.8%	7.9%	2.9%	0.4%
Danforth Village	445	86	48	7	83.4%	10.4%	5.5%	0.7%
Trinity-Bellwoods	220	42	13	8	84.9%	10.4%	3.0%	1.7%
Roncesvalles	419	78	36	8	84.5%	10.1%	4.5%	0.9%
Lawrence Park South	2238	543	77	242	80.7%	12.6%	1.7%	4.9%

(Jermyn, 2014)

METHODOLOGY – PHASE 1: ADDITIONAL ARCHTYPE MODEL

- Detached homes spanned 50%, semi-detached homes spanned 27%, and row houses spanned 13%
  - New century-semi archetype model was developed

	# of Building by Single Family Housing Type		
Name	**Single-Detached**	**Semi-Detached**	**Row**
North Riverdale	785	1205	135
Danforth village	665	1220	25
Trinity-Bellwoods	320	720	1000
Roncesvalles	630	995	360
Lawrence Park South	3415	110	25

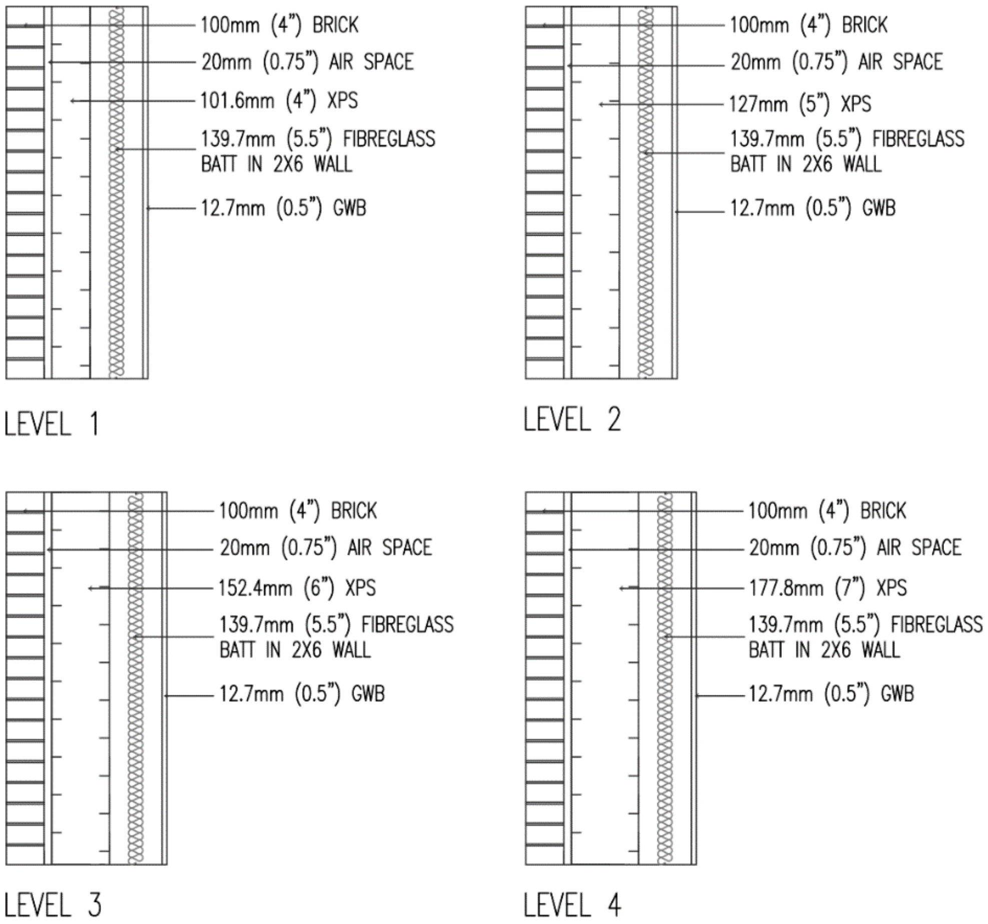
(Jermyn, 2014)

METHODOLOGY – PHASE 2: RETROFIT STRATEGIES

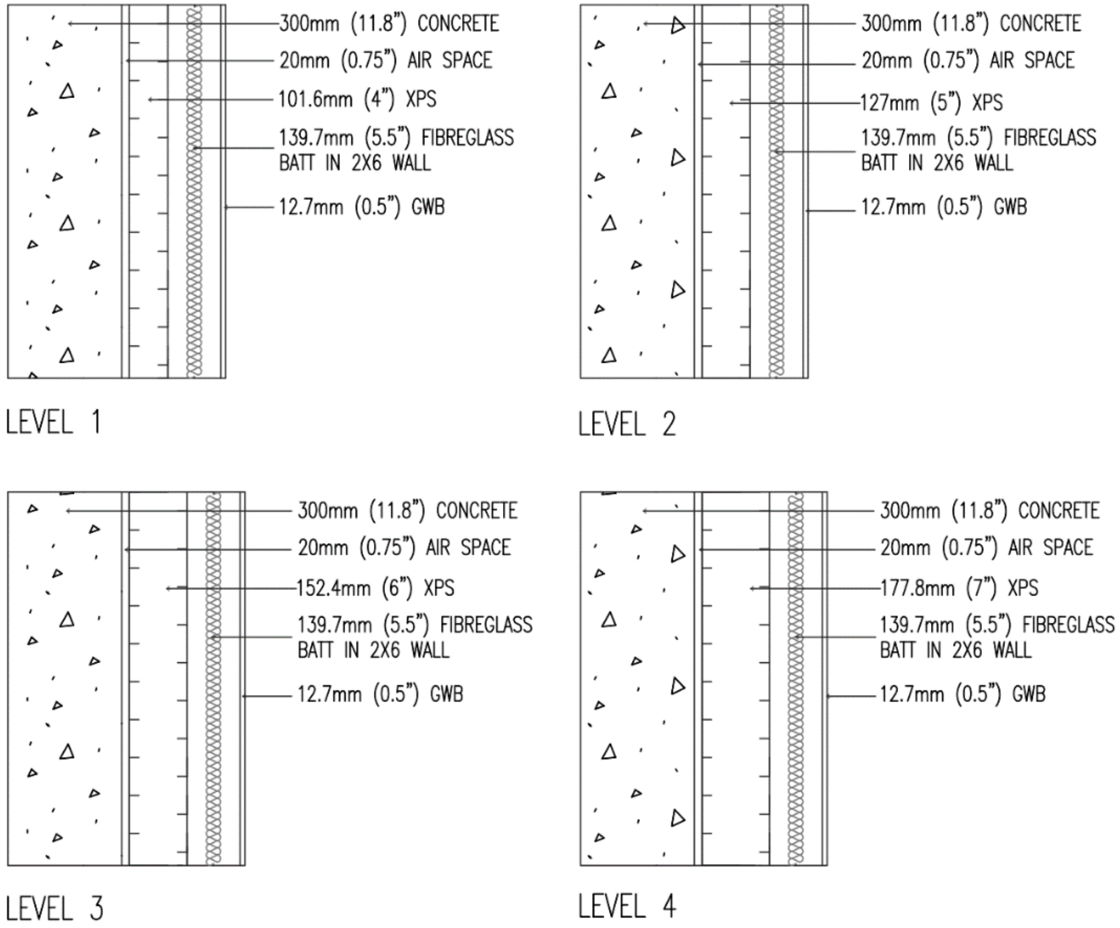
- Baseline values are from work performed by Blaszak, Jermyn, Lawrence, and Skarupa
- Retrofit levels range from PHIUS minimum to high performance values analyzed in similar research studies

	Century Detached	Century-Semi	Wartime	Retrofit Design Variables			
Retrofit Parameter	**Baseline**	**Baseline**	**Baseline**	**Level 1**	**Level 2**	**Level 3**	**Level 4**
Above Grade Walls (m^2·K/W)	1.01	1.01	1.65	7.22	8.10	8.98	9.86
Below Grade Walls (m^2·K/W)	0.55	0.55	0.83	7.22	8.10	8.98	9.86
Roof (m^2·K/W) - Century	2.64	2.64	-	12.86	13.91	14.97	16.03
Roof (m^2·K/W) - Wartime	-	-	3.58	12.33	13.74	14.79	15.85
Slab (m^2·K/W)	0.06	0.06	0.06	3.52	4.40	5.28	6.16
Window U-Factor (W/m^2K)	2.69	2.69	2.69	0.74	0.68	0.62	0.57
Mech. Ventilation Efficiency	N/A	N/A	N/A	82% HRV	83% ERV	88% HRV	91% HRV
Heating and Cooling (ASHP COP)	N/A	N/A	N/A	3.05	3.5	3.85	4.35
ACH at 50Pa	10.54	11.7	8.17	0.6			

METHODOLOGY – WARTIME WALL ASSEMBLIES



Above Grade Walls



Below Grade Walls

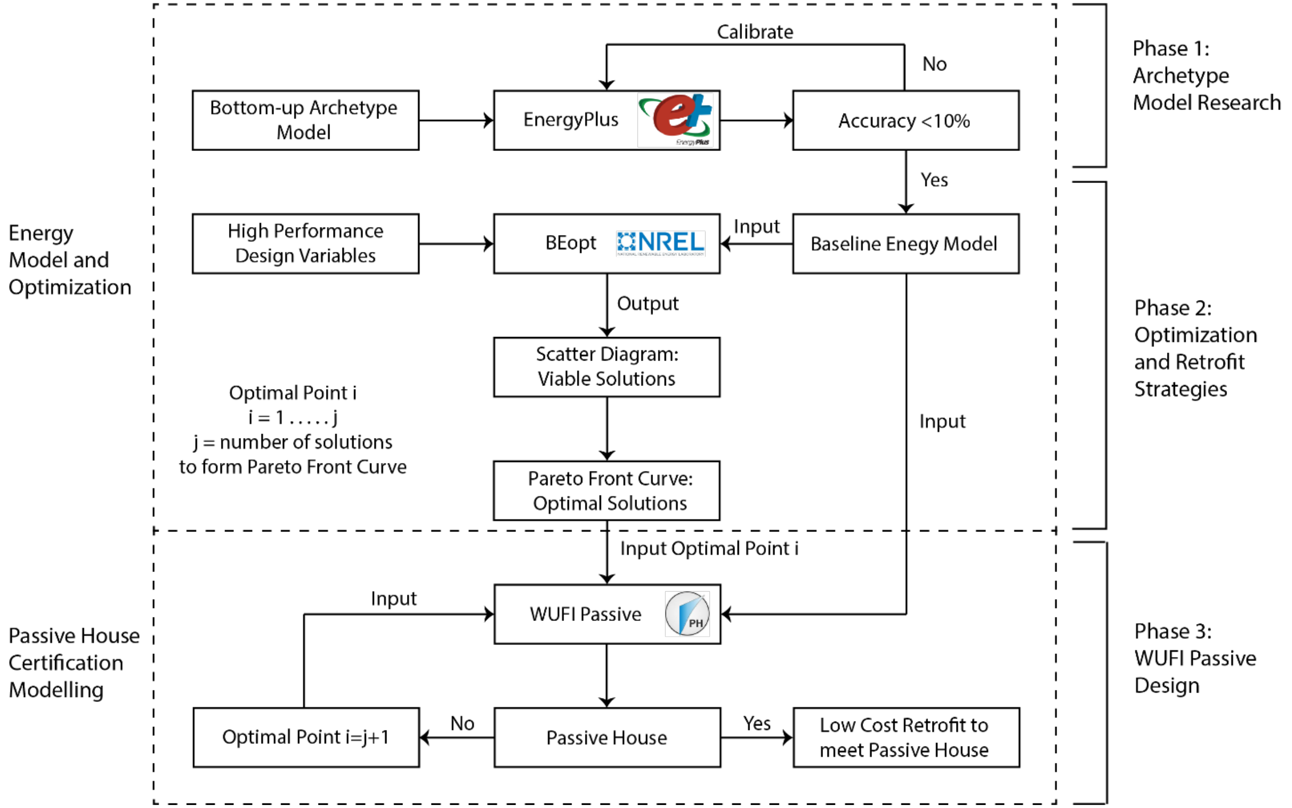
METHODOLOGY – PHASE 3: WUFI PASSIVE

- Baseline models are recreated in WUFI Passive
- Assumptions were utilized to satisfy inputs in energy modelling program
- Energy use calculations are not as accurate as other modelling programs such as EnergyPlus
- Pareto optimal configurations are implemented in WUFI Passive to test if the retrofit homes meet Passive House
- Space conditioning targets shown below:

Name	Century Detached	Century-Semi	Wartime
Envelope (m^2) / iCFA (m^2)	1.98	2.31	2.90
iCFA (m^2) / person	60	41	34
Annual Heating Demand (kWh/m^2yr)	19.9	23.3	31.5
Annual Cooling Demand (kWh/m^2yr)	11.8	15.0	27.7
Peak Heating Load (W/m^2)	15.8	18.8	25.0
Peak Cooling Load (W/m^2)	7.2	8.9	13.4

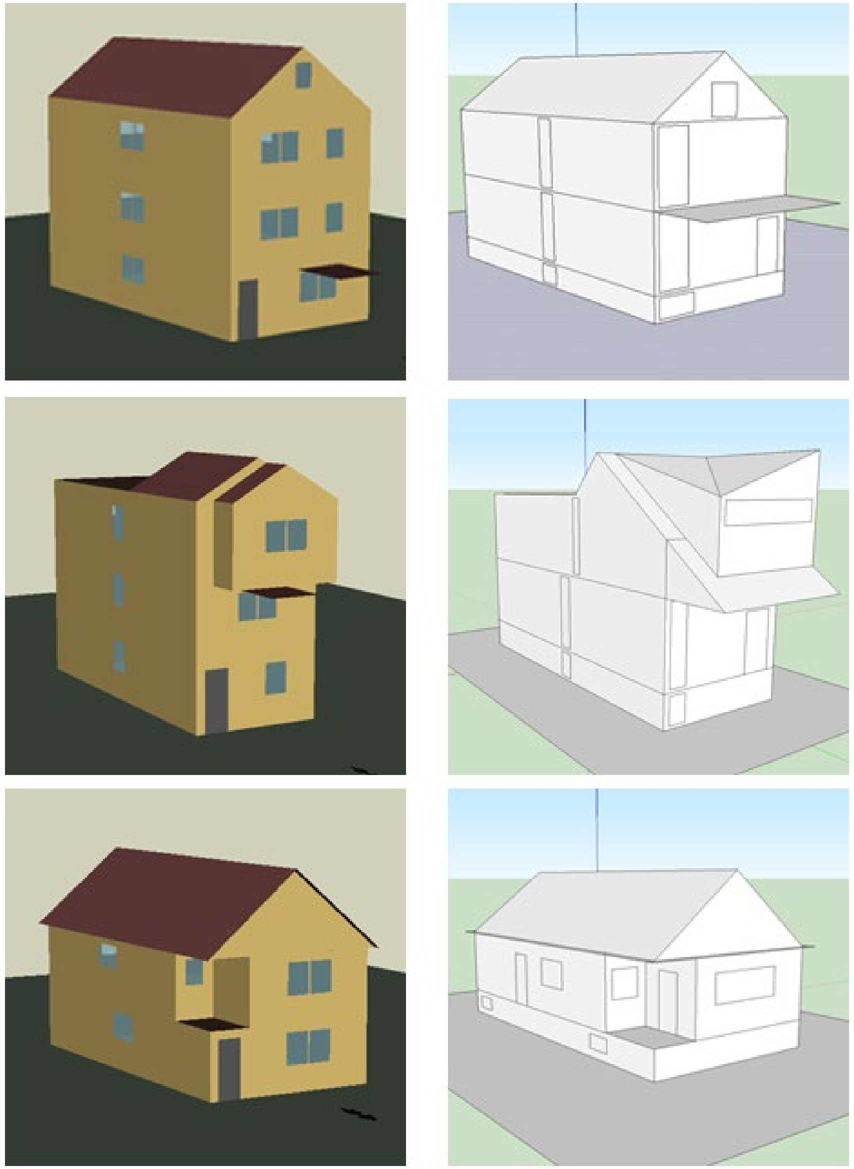
RESULTS

- Phase 1: Comparison of baseline EUI
- Phase 2: Output retrofit strategies from BEopt are analyzed
- Phase 3: Pareto optimal strategies are input into WUFI Passive to test the retrofit strategies against the space conditioning criteria



RESULTS AND DISCUSSION – PHASE 1: BASELINE MODELS

- Limitations in baseline models in BEopt:
  - Geometry was oversimplified
  - Below grade constructions were shifted to above grade
- Limitations in WUFI Passive:
  - Internal constructions were omitted
  - Energy use calculations are different than other programs



RESULTS AND DISCUSSION – PHASE 1: COMPARISON OF EUI

- Both BEopt and EnergyPlus use the same simulation engine
- Difference in EUI between BEopt and EnergyPlus
  - Oversimplification of geometry
  - Increase exposure to external air
- Difference in EUI between WUFI Passive and EnergyPlus
  - Different simulation engines
  - Does not calculate interior air flow

	Energy Use Intensity (kWh/m^{2}yr)			**% Difference in EUI**	
Name	Energy Plus	BEopt	WUFI Passive	BEopt to Energy Plus	WUFI Passive to Energy Plus
Century Detached	200	215	260	7.0	23.1
Century-Semi	226	237	243	4.6	7.0
Wartime	215	208	200	-3.4	-7.5

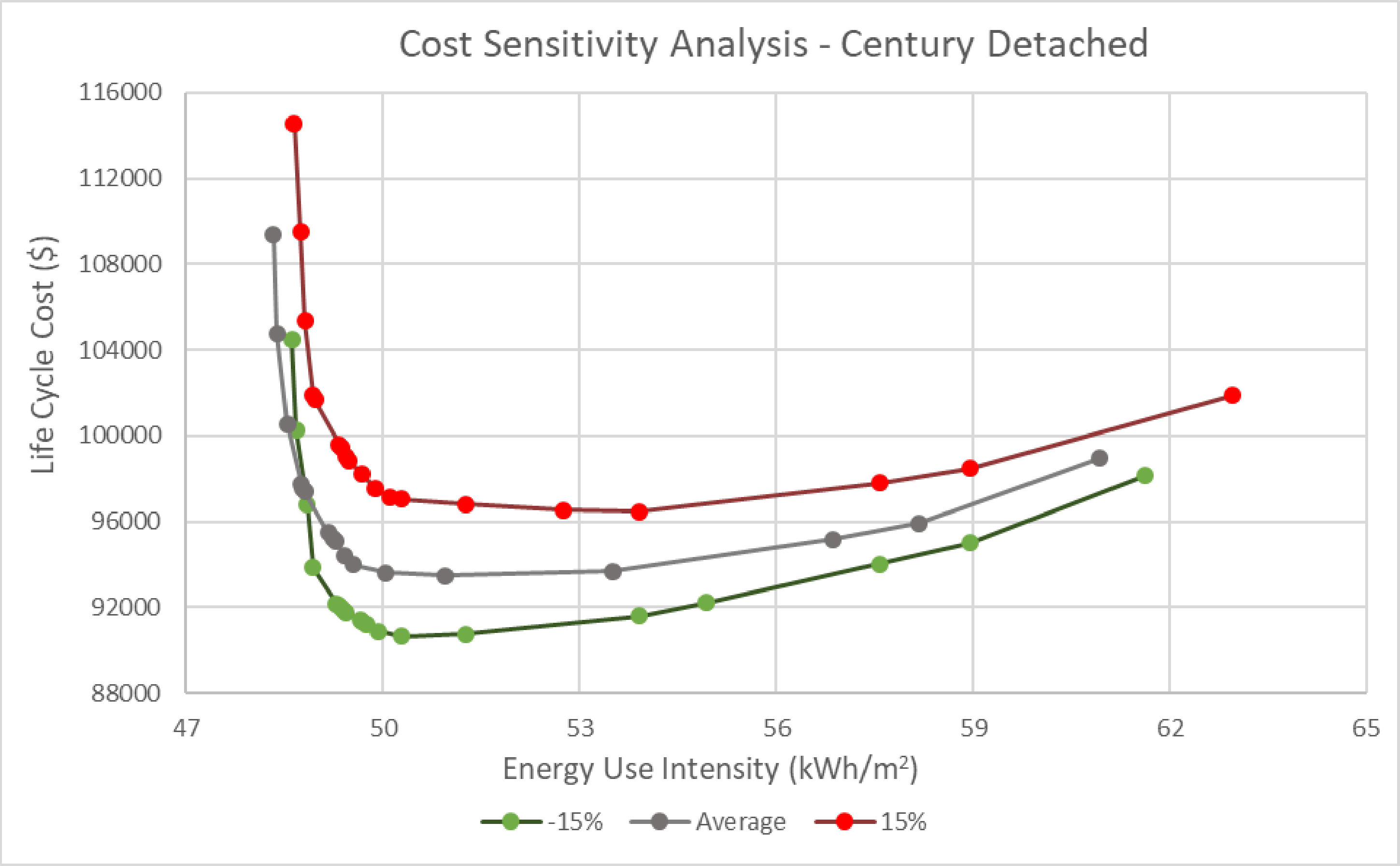
RESULTS AND DISCUSSION – PHASE 2: OPTIMAL STRATEGIES

Cost Sensitivity Analysis

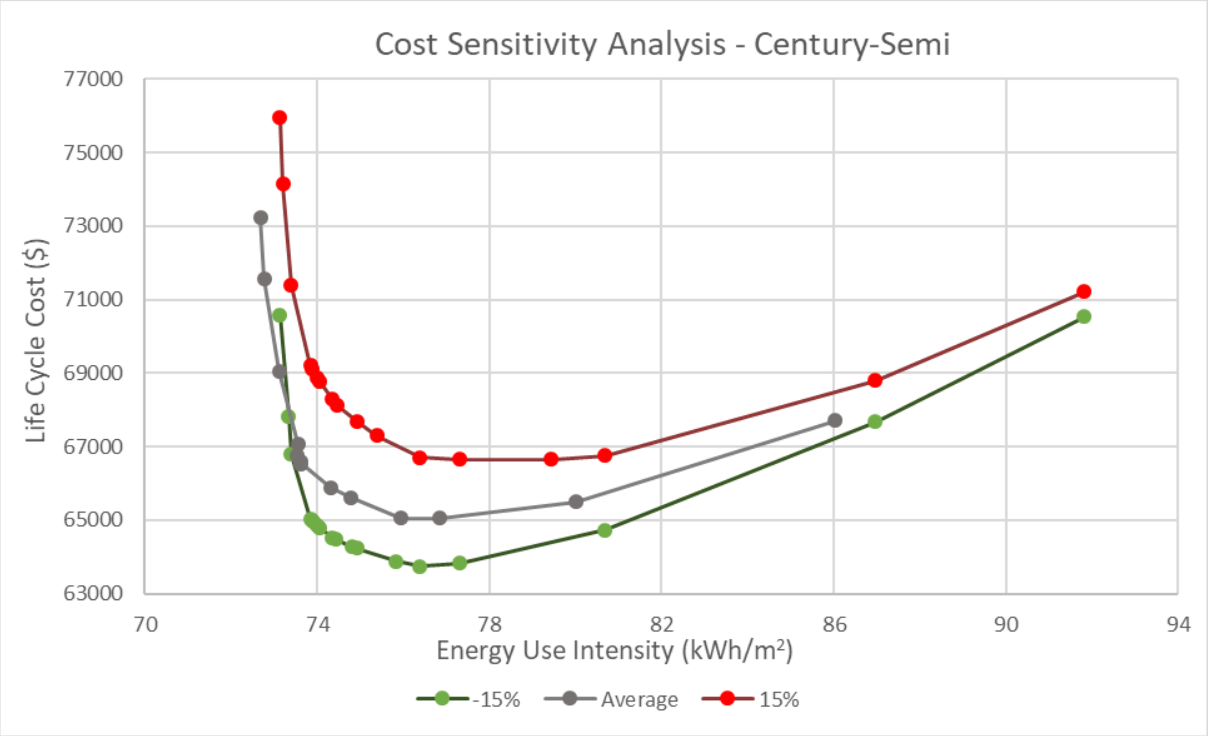
- Costing data input into the BEopt are considered average values
- Increase and decrease are financial values and capital costs by 15%

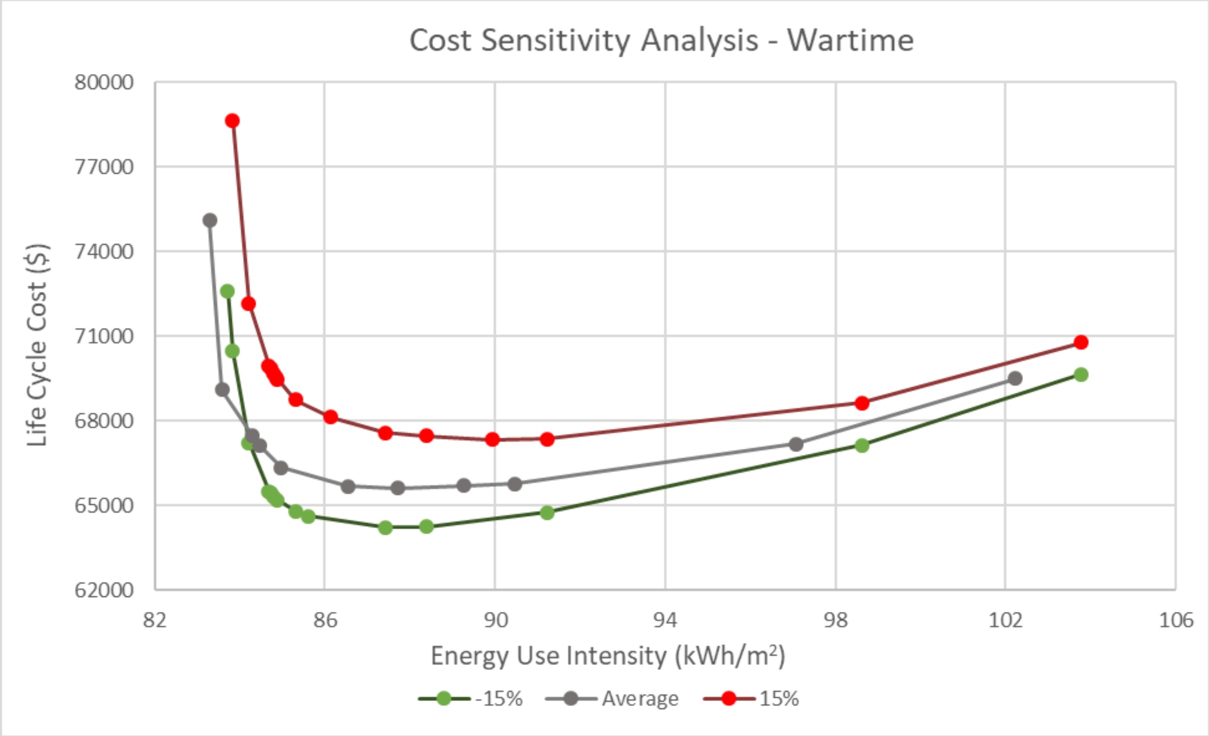
Financial Parameter	**Minimum (-15%)**	**Average**	**Maximum (+15%)**
Inflation Rate	2.04	2.40%	2.76
Discount Rate	2.55	3.00%	3.45
Mortgage Interest Rate	3.4	4.00%	4.6
Marginal Income Tax Rate	23.8	28%	32.2
Electricity Utility Cost	6.8 $/month	8.00 $/month	9.2 $/month
Natural Gas Utility Cost	6.8 $/month	8.00 $/month	9.2 $/month

RESULTS AND DISCUSSION – COST SENSITIVITY ANALYSIS

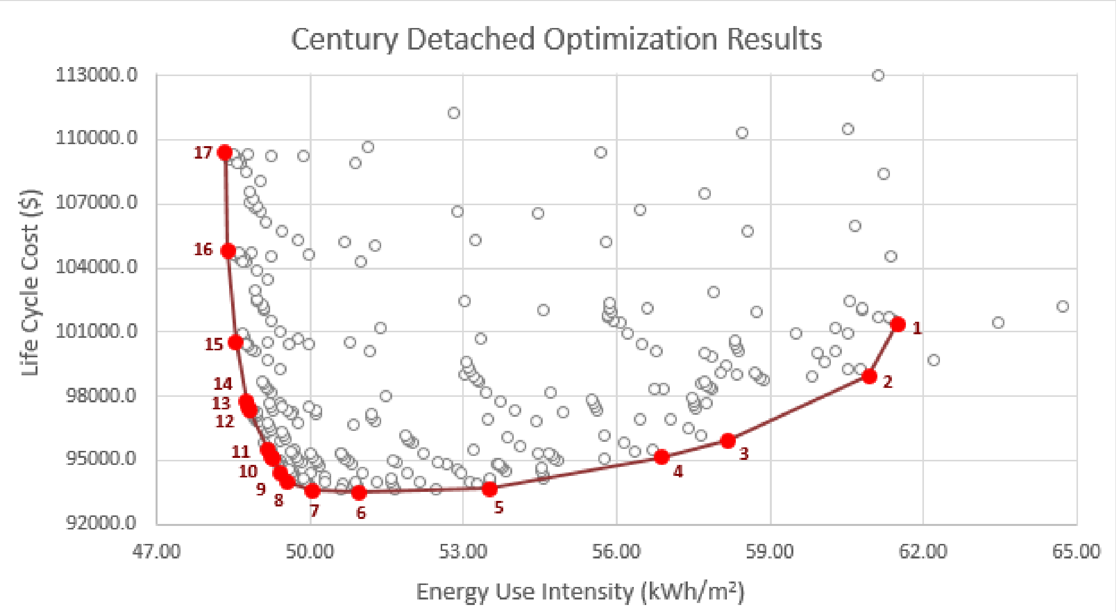


RESULTS AND DISCUSSION – COST SENSITIVITY ANALYSIS



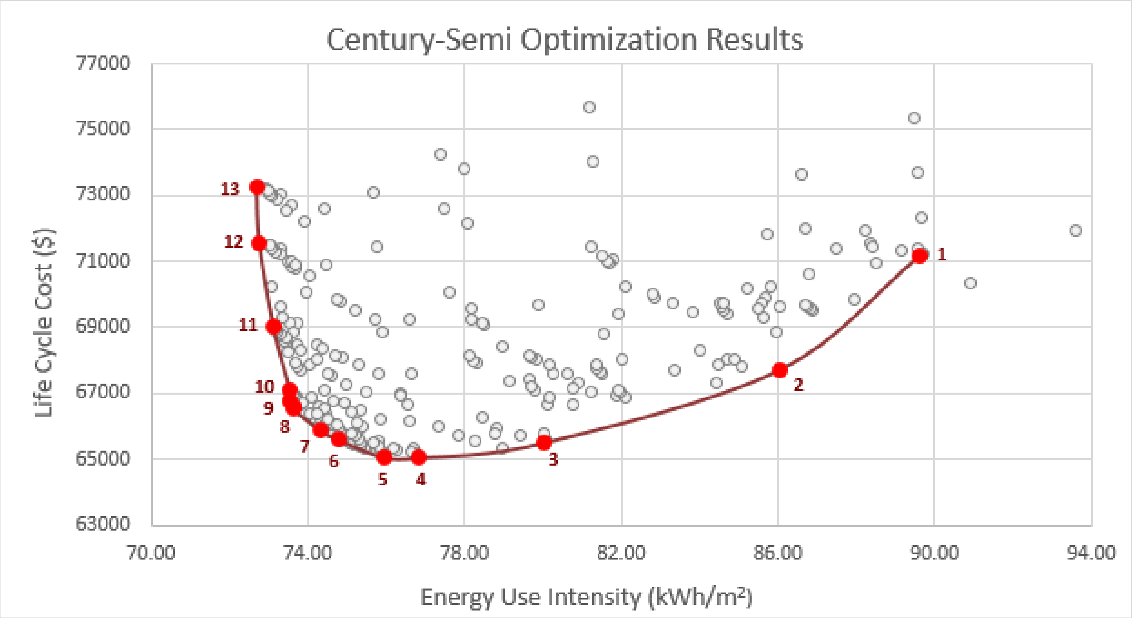


RESULTS AND DISCUSSION – PHASE 2: OPTIMAL STRATEGIES



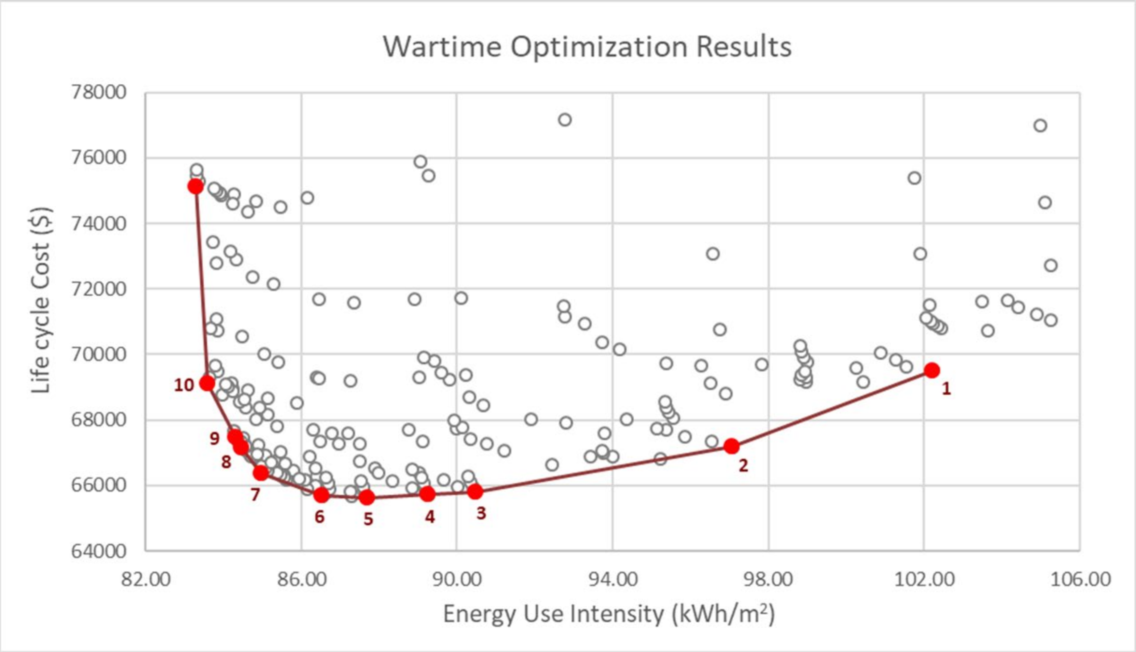
Pareto Point	Walls	Roof	Slab	Windows	Mech. Ventilation	Heating and Cooling	Air Leakage	EUI (kWh/m^2)
Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	295.82
Point 1	Level 1	Baseline	Baseline	Level 1	Level 2	Level 2	Level 1	60.93
Point 2	Level 1	Baseline	Baseline	Level 1	Level 3	Level 1	Level 1	58.18
Point 3	Level 1	Baseline	Baseline	Level 1	Level 3	Level 2	Level 1	56.87
Point 4	Level 1	Baseline	Level 1	Level 1	Level 3	Level 2	Level 1	53.51
Point 5	Level 1	Level 1	Level 1	Level 1	Level 3	Level 2	Level 1	50.96
Point 6	Level 1	Level 1	Level 1	Level 1	Level 3	Level 4	Level 1	50.05
Point 7	Level 2	Level 1	Level 1	Level 1	Level 3	Level 4	Level 1	49.56
Point 8	Level 3	Level 1	Level 1	Level 1	Level 3	Level 4	Level 1	49.43
Point 9	Level 4	Level 2	Level 1	Level 1	Level 3	Level 4	Level 1	49.28
Point 10	Level 4	Level 3	Level 1	Level 1	Level 3	Level 4	Level 1	49.23
Point 11	Level 4	Level 4	Level 2	Level 1	Level 3	Level 4	Level 1	49.17
Point 12	Level 4	Level 4	Level 2	Level 1	Level 4	Level 4	Level 1	48.81
Point 13	Level 4	Level 4	Level 3	Level 1	Level 4	Level 4	Level 1	48.78
Point 14	Level 4	Level 4	Level 4	Level 1	Level 4	Level 4	Level 1	48.76
Point 15	Level 4	Level 4	Level 2	Level 2	Level 4	Level 4	Level 1	48.54
Point 16	Level 4	Level 4	Level 4	Level 3	Level 4	Level 4	Level 1	48.39
Point 17	Level 4	Level 4	Level 4	Level 4	Level 4	Level 4	Level 1	48.34

RESULTS AND DISCUSSION – PHASE 2: OPTIMAL STRATEGIES



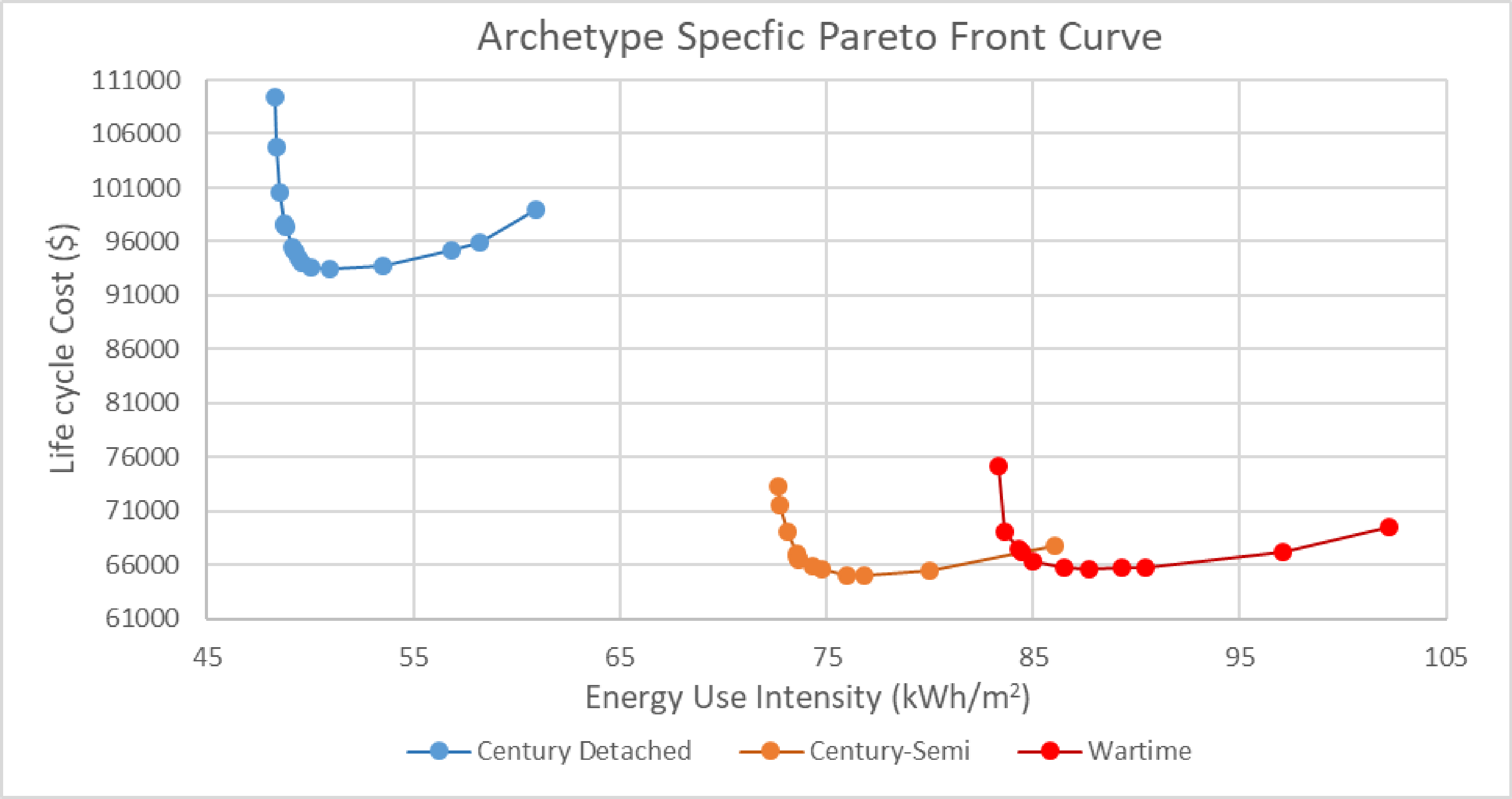
Pareto Point	Walls	Roof	Slab	Windows	Mech. Ventilation	Heating and Cooling	Air Leakage	EUI (kWh/m^2)
Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	275.34
Point 1	Level 1	Baseline	Baseline	Level 1	level 3	Level 1	Level 1	86.04
Point 2	Level 1	Baseline	Level 1	Level 1	level 3	Level 1	Level 1	80.00
Point 3	Level 1	Level 1	Level 1	Level 1	level 3	Level 1	Level 1	76.84
Point 4	Level 1	Level 1	Level 1	Level 1	Level 3	Level 2	Level 1	75.95
Point 5	Level 1	Level 2	Level 1	Level 1	Level 3	Level 4	Level 1	74.78
Point 6	Level 2	Level 2	Level 1	Level 1	Level 3	Level 4	Level 1	74.32
Point 7	Level 4	Level 1	Level 1	Level 1	Level 3	Level 4	Level 1	73.63
Point 8	Level 4	Level 2	Level 1	Level 1	Level 3	Level 4	Level 1	73.61
Point 9	Level 4	Level 4	Level 1	Level 1	Level 3	Level 4	Level 1	73.54
Point 10	Level 4	Level 4	Level 4	Level 1	Level 3	Level 4	Level 1	73.55
Point 11	Level 4	Level 4	Level 4	Level 1	Level 4	Level 4	Level 1	73.12
Point 12	Level 4	Level 4	Level 4	Level 3	Level 4	Level 4	Level 1	72.77
Point 13	Level 4	Level 4	Level 4	Level 4	Level 4	Level 4	Level 1	72.69

RESULTS AND DISCUSSION – PHASE 2: OPTIMAL STRATEGIES



Pareto Point	Walls	Roof	Slab	Windows	Mech. Ventilation	Heating and Cooling	Air Leakage	EUI (kWh/m^2)
Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	244.06
Point 1	Level 1	Baseline	Baseline	Level 1	Level 2	Level 1	Level 1	102.23
Point 2	Level 1	Baseline	Baseline	Level 1	Level 3	Level 1	Level 1	97.07
Point 3	Level 1	Baseline	Level 1	Level 1	Level 3	Level 1	Level 1	90.47
Point 4	Level 1	Baseline	Level 1	Level 1	Level 3	Level 2	Level 1	89.26
Point 5	Level 1	Level 1	Level 1	Level 1	Level 3	Level 1	Level 1	87.70
Point 6	Level 1	Level 1	Level 1	Level 1	Level 3	Level 2	Level 1	86.53
Point 7	Level 2	Level 1	Level 1	Level 1	Level 3	Level 4	Level 1	84.98
Point 8	Level 4	Level 4	Level 1	Level 1	Level 3	Level 4	Level 1	84.46
Point 9	Level 4	Level 4	Level 3	Level 1	Level 3	Level 4	Level 1	84.30
Point 10	Level 4	Level 4	Level 1	Level 1	Level 4	Level 4	Level 1	83.59
Point 11	Level 4	Level 4	Level 1	Level 4	Level 4	Level 4	Level 1	83.29

RESULTS AND DISCUSSION – PHASE 2: OPTIMAL STRATEGIES



RESULTS AND DISCUSSION – PHASE 3: PASSIVE HOUSE

- Optimal configurations from BEopt are crossed over into WUFI Passive
- Retrofits are tested against the space conditioning criteria and to meet source energy requirements of 3840 kwh/person
- Renewable energy is utilized as a final design strategy if necessary to meet source energy requirements

RESULTS AND DISCUSSION – PHASE 3: LOW COST DESIGN STRATEGY

Century Detached

Pareto Point	Heating Demand (kWh/m^2)	Cooling Demand (kWh/m^2)	Heating Load (W/m^2)	Cooling Load (W/m^2)	Source Energy (kWh/Person)	Energy Intensity (kWh/m^2)
Baseline	221.56	5.39	84.38	8.06	43,310	259.88
Point 1	134.09	4.32	56.02	7.03	12,123	72.74
Point 2	132.82	4.03	55.60	6.82	12,524	75.15
Point 3	132.82	4.03	55.60	6.82	11,392	68.35
Point 4	30.00	7.03	18.64	6.36	6,635	39.81
Point 5	17.96	7.60	14.42	5.97	6,082	36.49
Point 6	17.96	7.60	14.42	5.97	5,995	35.97
Point 7	16.86	7.73	14.03	5.97	5,951	35.71
Point 8	16.03	7.84	13.71	5.97	5,916	35.5
Point 9	15.11	7.95	13.37	5.96	5,878	35.27
Point 10	14.93	7.97	13.30	5.95	5,870	35.22
Point 11	13.50	8.15	12.73	5.94	5,812	34.87
Point 12	12.87	8.15	12.47	5.94	5,773	34.64
Point 13	12.01	8.27	12.12	5.94	5,738	34.43
Point 14	11.39	8.37	11.86	5.93	5,712	34.28
Point 15	12.44	8.22	12.30	5.94	5,755	34.53
Point 16	10.56	8.51	11.52	5.94	5,678	34.07
Point 17	10.18	8.57	11.36	5.94	5,663	33.98

RESULTS AND DISCUSSION – PHASE 3: LOW COST DESIGN STRATEGY

Wartime

Pareto Point	Heating Demand (kWh/m^2)	Cooling Demand (kWh/m^2)	Heating Load (W/m^2)	Cooling Load (W/m^2)	Source Energy (kWh/Person)	Energy Intensity (kWh/m^2)
Baseline	146.67	5.95	56.92	8.98	19,058	199.76
Point 1	52.44	3.05	24.92	6.39	5,997	62.86
Point 2	50.71	2.93	24.30	6.28	5,711	59.86
Point 3	33.70	7.77	20.79	6.99	5,179	54.28
Point 4	33.70	7.77	20.79	6.99	5,043	52.86
Point 5	16.27	8.37	14.58	6.43	4,633	48.56
Point 6	16.27	8.37	14.58	6.43	4,568	47.88
Point 7	15.08	8.46	14.12	6.41	4,474	46.9
Point 8	12.12	8.68	12.95	6.34	4,405	46.17
Point 9	11.80	8.64	12.88	6.36	4,397	46.09
Point 10	11.24	8.68	12.58	6.34	4,373	45.84
Point 11	10.09	8.85	12.08	6.34	4,346	45.56

RESULTS AND DISCUSSION – PHASE 3: LOW COST DESIGN STRATEGY

Century Semi

Pareto Point	Heating Demand (kWh/m^2)	Cooling Demand (kWh/m^2)	Heating Load (W/m^2)	Cooling Load (W/m^2)	Source Energy (kWh/Person)	Energy Intensity (kWh/m^2)
Baseline	194.25	2.11	64.84	0.27	19,487	242.5
Point 1	83.82	0.61	29.49	0.00	5,428	67.54
Point 2	29.24	2.77	17.08	3.89	3,990	49.65
Point 3	18.24	3.03	13.24	3.68	3,700	46.04
Point 4	18.24	3.03	13.24	3.68	3,638	45.27
Point 5	18.03	3.04	13.17	3.68	3,574	44.47
Point 6	16.51	3.11	12.64	3.67	3,543	44.09
Point 7	14.47	3.22	11.92	3.67	3,503	43.59
Point 8	14.27	3.23	11.84	3.66	3,499	43.54
Point 9	13.95	3.24	11.73	3.66	3,493	43.46
Point 10	12.78	3.49	11.40	3.79	3,469	43.17
Point 11	11.98	3.49	11.10	3.79	3,446	42.88
Point 12	11.43	3.54	10.89	3.79	3,435	42.74
Point 13	11.20	3.56	10.80	3.79	3,430	42.69

RESULTS AND DISCUSSION – PHASE 3: RENEWABLE ENERGY

- Solar panels were utilized on century detached and wartime archetypes to meet source energy requirements
- PV systems ranging from 0.5 kW to 7 kW were tested on the homes
- 1 kW system was best suited for the detached home and 0.5 kW was best suited for the wartime archetype

Housing Type	PV Size	Renewable Energy Produced (kWh/yr)	Capital Cost	Life Cycle Cost
Century Detached	1.0 kW	3704.4	$4,239	-$536
Wartime	0.5 kW	1846.35	$2,675	$247

Pareto Point	Detached	Wartime
Baseline	43,310	19,058
Point 1	12,123	5,997
Point 2	12,524	5,711
Point 3	11,392	5,179
Point 4	6,635	5,043
Point 5	3,528	3,341
Point 6	3,402	3,275
Point 7	3,358	3,182
Point 8	3,323	3,114
Point 9	3,285	3,106
Point 10	3,277	3,082
Point 11	3,219	3,055
Point 12	3,180	N/A
Point 13	3,145	N/A
Point 14	3,119	N/A
Point 15	3,162	N/A
Point 16	3,085	N/A
Point 17	3,070	N/A

RESULTS AND DISCUSSION – PHASE 3: LOW COST DESIGN STRATEGY

- Final results from the multi-objective optimization to meet Passive House for the lowest life cycle cost:

Pareto Optimal Point	Heating Demand (kWh/m^2)	Cooling Demand (kWh/m^2)	Heating Load (W/m^2)	Cooling Load (W/m^2)	Source Energy (kWh/Person)	Life Cycle Cost
Century Detached Point 5	17.96	7.6	14.42	5.97	3,528	$92,950
Century-Semi Point 3	18.24	3.03	13.24	3.68	3,700	$65,053
Wartime Point 5	16.27	8.37	14.58	6.43	3,341	$65,877

RESULTS AND DISCUSSION – PHASE 3: OPTIMAL DESIGN STRATEGY

	Century Detached		Century Semi		Wartime	
Pareto Point	**NPV ($)**	**MIRR (%)**	**NPV ($)**	**MIRR (%)**	**NPV ($)**	**MIRR (%)**
Point 1	-$17,718	2.08	-$5,018	3.94	-$18,429	0.81
Point 2	-$14,673	2.49	-$2,805	4.64	-$16,107	1.16
Point 3	-$13,911	2.59	-$2,358	4.86	-$14,708	2.03
Point 4	-$12,424	3.13	-$2,364	4.86	-$14,638	2.04
Point 5	-$12,241	3.48	-$2,912	4.74	-$14,553	2.38
Point 6	-$12,360	3.47	-$3,198	4.71	-$14,604	2.37
Point 7	-$12,719	3.50	-$3,834	4.65	-$15,284	2.38
Point 8	-$13,192	3.52	-$3,909	4.64	-$16,079	2.52
Point 9	-$13,825	3.54	-$4,062	4.62	-$16,409	2.56
Point 10	-$13,951	3.54	-$4,382	4.59	-$18,034	2.36
Point 11	-$14,242	3.55	-$6,355	4.28	-$24,029	1.73
Point 12	-$16,126	3.39	-$8,881	3.90	N/A	N/A
Point 13	-$16,294	3.40	-$10,545	3.67	N/A	N/A
Point 14	-$16,470	3.40	N/A	N/A	N/A	N/A
Point 15	-$19,317	3.10	N/A	N/A	N/A	N/A
Point 16	-$23,521	2.78	N/A	N/A	N/A	N/A
Point 17	-$28,169	2.43	N/A	N/A	N/A	N/A

RESULTS AND DISCUSSION – PHASE 3: OPTIMAL DESIGN STRATEGY

- Design configurations with the most optimal ratio of life cycle cost to energy saved:

Pareto Optimal Point	Heating Demand (kWh/m^2)	Cooling Demand (kWh/m^2)	Heating Load (W/m^2)	Cooling Load (W/m^2)	Source Energy (kWh/Person)	Life Cycle Cost
Century Detached Point 11	13.50	8.15	12.73	5.94	3,219	$94,951
Century-Semi Point 3	18.24	3.03	13.24	3.68	3,700	$65,053
Wartime Point 9	11.80	8.64	12.88	6.36	3,106	$67,732

RESULTS AND DISCUSSION –
PHASE 3: STANDARD VS PASSIVE HOUSE RETROFIT

- Design configurations with the most optimal ratio of life cycle cost to energy saved:

Century Detached	Life Cycle Cost	EUI (kWh/m^{2}yr)
Lowest Cost Retrofit	$92,950	36.49
Cost Optimal Retrofit	$94,951	34.87
Standard Retrofit	$71,498	89.21

Century-Semi	Life Cycle Cost	EUI (kWh/m^{2}yr)
Lowest Cost Retrofit	$65,053	46.04
Cost Optimal Retrofit	$65,053	46.04
Standard Retrofit	$56,124	127.18

Wartime	Life Cycle Cost	EUI (kWh/m^{2}yr)
Lowest Cost Retrofit	$65,877	48.56
Cost Optimal Retrofit	$67,732	46.09
Standard Retrofit	$53,336	135.17

FUTURE WORK

- Research should be applied to 1970’s OBC and modern homes
- Apply the research to houses in other municipalities and in various climate zones
- Larger range of thermal performance values
  - Increase range in thermal performance can allow the work to be adapted to newer homes
- Apply research to new developments instead of only on existing homes
- Various objective functions such as occupant comfort and carbon emissions to show added benefit of achieving Passive House

CONCLUSIONS

- Archetype models that represent Toronto’s housing stock can be retrofit to meet Passive House certification
- Retrofit strategies vary depending on cost data and specific geometry
- Achieving PHIUS standards is more economically feasible when analyzed through life cycle costs
- Achieving Passive House allows homes to be more:
    - Comfortable
    - Resilient
    - Economically friendly
    - Healthier

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