Evaluation of the sensitivity of prescriptive building energy code energy conservation measures

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Abstract

There are ongoing efforts to develop tiered energy codes for buildings to reduce energy consumption of new construction in Canada. For housing and small buildings, there is a desire to maintain prescriptive compliance paths that will nominally meet the performance objectives of the tiers. Establishing prescriptive requirements that correlate to a set energy savings is a non-trivial task since the efficacy of energy conservation measures (ECMs) varies across different climates and built forms. This study analyzed how consistent, or sensitive, the energy performance of different prescriptive envelope ECMs are using 240 new construction housing archetypes representing five climate zones. Parametric simulations were conducted using the Housing Technology Assessment Platform (HTAP), and both energy performance and incremental construction costs were determined. The analysis showed that prescriptive airtightness and exterior wall insulation measures provide the highest performance per variation across built-forms in all major Canadian climates.

Introduction

The built environment is identified in the Pan-Canadian Framework on Clean Growth and Climate Change (ECCC, 2016) as a target for reducing national greenhouse gas (GHG) emissions to meet Paris Climate Agreement commitments. Part of the strategy outlined in the framework is the implementation of new model building codes to improve the energy performance of new construction. Currently in Canada there are two model codes that describe minimum energy performance of buildings: the 2017 National Energy Code of Canada for Buildings (NECB) (CCBFC, 2017), and Section 9.36 of the 2015 National Building Code of Canada (CCBFC, 2015). The latter is only applicable to housing and small buildings, while the NECB can be applied to all buildings. Both codes use a two path compliance approach: prescriptive and performance. The prescriptive path provides minimum performance criteria for building envelope components, HVAC, and domestic hot water systems. Compliance is demonstrated by inspecting drawings and the building to ensure that each component meets the minimum requirements of the code. There are also provisions for trade-offs, where one component may be below minimum requirements up to a certain amount if a different component exceeds minimum requirements by a certain amount. The performance path requires builders to demonstrate that their building design consumes as much or less annual energy than a similar reference building constructed to minimum prescriptive requirements. Compliance is typically demonstrated using building energy simulation tools that have been benchmarked against ASHRAE 140 (ASHRAE, 2014). Model boundary conditions, such as thermostat setpoints and internal gains, are detailed in the code. In practice, the performance path is typically used for large commercial buildings and apartments, whereas small residential builders tend to use the Section 9.36 prescriptive path.

The Canadian Commission on Building and Fire Codes (CCBFC) has stated that a potential way to implement new energy codes is to use a "step" or "tiered" approach (CCBFC, 2016). Such a building energy code has already been adopted in British Columbia (Province of British Columbia, 2017). Tiers signal to the industry the direction the codes are moving in so that they may better prepare for changes. There is a desire to maintain prescriptive and performance pathways in this tiered approach to enable flexibility for code users. Currently for housing and small buildings two proposed code changes have been submitted to implement prescriptive and performance-based tiers (NRC, 2019). The performance tiers use percentage better than reference building for the tier targets, where percent better is measured in both overall energy and envelope performance. The prescriptive tiers adopted an approach where a code user selects from a set of energy conservation measures (ECMs). Each ECM is allocated a number of points which are representative of the ECMs energy savings potential. Each tier defines the total number of ECM points required to comply with the tier, and the savings are intended to be aligned with the performance tiers.

Improvements in minimum performance criteria provided in the code does not necessarily scale directly with annual energy savings, however, since many of the performance criteria metrics are dimensional and/or not normalized. For example, fenestration performance is described in the code using a maximum U-value [$W/m^2 \cdot K$]. The efficacy of improving overall building performance, via lower U-value, therefore varies with area of installed fenestration. This creates challenges for defining ECM points for envelope improvements using component performance metrics currently used in the code. Building performance simulation (BPS) tools are useful since they enable assessment of ECMs over a broad range of built forms and climate scenarios. The focus of this paper is assessing the consistency of performance, or sensitivity, of envelope ECMs applied to a broad range of climates and built forms representative of the new construction housing stock in Canada. Nominal performance of ECMs is also investigated.

Sensitivity in building design

During building design and optimization phases the actual operating conditions are uncertain; particularly climate conditions (De Wilde and Coley, 2012), and occupancy (Yan et al., 2015). This often leads to discrepancies between the estimated and actual building performance. Kotireddy et al. (2018) noted that the deviation can be significant for low-energy buildings (Maier et al., 2009; Martinaitis et al., 2015). To account for these uncertainties in building optimization analyses researchers such as Kotireddy et al. (2019) have adopted "robustness" indicators. Hoes et al. (2009) defined design robustness as "the sensitivity of identified performance indicators of a building design for errors in the design assumptions." There are principally two types of robustness assessment approaches used in literature (Kotireddy et al., 2018): probabilistic, and non-probabilistic. The former approach assumes that the uncertainty probabilities are known, e.g. Van Gelder et al. (2014) and Cheng et al. (2017). Kotireddy et al. (2018) noted that often the uncertainties for buildings at design stage are difficult to quantify. They therefore adopted a non-probabilistic approach using scenario analysis, where optimal net-zero building designs are simulated under different climate, occupancy, policy, and space usage scenarios to quantify their robustness.

For this study, the concepts of robustness and non-probabilistic sensitivity analyses are adopted for analyzing prescriptive measures which may be considered as ECMs for the tierd prescriptive building code. One of the largest sources of uncertainty when assessing the impacts of prescriptive measures is that the building code does not regulate built form. Per sentence 1.3.3.3.(1) Section 9.36 energy efficiency codes only apply to buildings for three storeys or less, with each storey having a floor area no greater than 600 m^2. Beyond that criteria there are no constraints on build form in terms of parameters such as floorplan shape, window-to-wall ratio, etc. Therefore, the scenarios used in this robustness assessment are a variety of built forms reflective what is being built in the current market across Canada. Subsection 9.36.5 prescribes the occupant behaviour modelling parameters to be used to demonstrate compliance, and therefore different occupancy and building usage scenarios are not developed for this study. Additionally, since energy performance is characterized in Section 9.36 as the difference between reference and proposed where both are subjected to identical boundary conditions, different climate and occupancy scenarios are assumed to not have a significant impact on performance.

Kotireddy et al. (2019) identified two robustness indicators applicable to optimal low-energy building design: max-min, and minimax regret defined by Savage (1951). For the min-max method, the maximum and minimum performance of each design d_i is determined over all considered scenarios. The difference between the max and min for each d_i is calculated (the performance spread), and most robust design is the one that has the minimum performance spread. The performance spread has the same units as the performance indicator and can be easily interpreted. For the minimax regret method the minimum performance across all d_i for a given scenario S_j is determined (A_j). The regret for each d_i in scenario S_j is then calculated as the design's performance under S_j minus A_j. The maximum regret is then determined for each d_i, and the most robust design is that which has the minimum design regret maximum. Additional details are omitted here for clarity, and the interested reader is directed to Kotireddy et al. (2019).

The previous work of Kotireddy et al. (2019) applied these robustness indicators as objectives to be minimized in low-energy design. In this application not all ECMs (designs) are expected or required to achieve the same level of energy performance. Therefore, the efficacy of the ECMs need to be evaluated for their robustness as well as their nominal performance. This paper proposes the use of coefficient of variation (CV) to quantify the sensitivity of ECMS. The CV for a given ECM is calculated as the ratio of the standard deviation of the ECM performance across all scenarios to the mean performance. The normalization of the spread is intended to facilitate equitable comparisons of ECMs achieving various nominal efficacy. The CVs are reported alongside mean ECM performance to provide more complete indication of ECM efficacy. The min-max robustness indicator, considered a consecutive metric (Kotireddy et al., 2019), is also used.

Methodology

This study used the Housing Technology Assessment Platform (HTAP) developed by NRCan (2015). The underlying BPS tool of HTAP is HOT2000 (NRCan, 2020) which uses a monthly bin method, along with hourly bin calculations for specific building components and mechanical systems, to calculate monthly and annual energy end-use consumption of residential buildings. HOT2000 was previously benchmarked against the Home Energy Rating System Building Energy Simulation Test (HERS BESTEST) (Haltrecht and Fraser, 1997), and more recently Parekh et al. (2018) evaluated version 11.3 was against ASHRAE Standard 140-2014 (ASHRAE, 2014). They found heating energy results were within the range of benchmarks listed in the standard, and stated overall energy consumption estimates were within acceptable ranges. They did, however, find that HOT2000 generally under-predicted cooling energy consumption. The current analysis did not consider cooling systems as they are not required in NBC 9.36 reference buildings unless the proposed building has one installed.

HTAP was developed to facilitate techno-economic parametric and optimization simulation studies. It is a combination of "[HOT2000], building stock data, energy conservation measures, rulesets and energy targets, economic data, and cloud computing to analyze numerous technology combinations and identify optimized design scenarios" (Asaee et al., 2019). One of the rulesets implemented into HTAP converts an input model file to an NBC 9.36 code-reference building. This functionality has been used to support the development of new building energy codes in Canada (Asaee et al., 2019), and is used in this study to establish baseline energy performance of current-code buildings. HTAP also contains an extensive library of ECMs that can be implemented into models. Currently, there are five classes of ECMs in HTAP: (i) airtightness, (ii) opaque and transparent envelope components, (iii) HVAC and domestic hot water systems, (iv) occupant and climate boundary conditions, and (v) model orientation. The specific ECMs considered in this study are described below.

The different scenarios considered in study are encapsulated by 240 new construction single-detached and double/row archetypes, described below. Each archetype is modified to comply with 2015 NBC Section 9.36 reference building modelling requirements. This conversion is performed automatically using a "ruleset" contained in HTAP. This ruleset, or subroutine, imports a HOT2000 model and updates the envelope, HVAC and domestic hot water systems, and operating and boundary conditons to comply with Subsection 9.36.5 modelling requirements. Minimum envelope performance characteristics are specified in the NBC based on building climate zone location, and whether a heat recovery ventilator (HRV) is installed. An explicit climate location can be provided to the rulset for assigning corresponding envelope performance characteristics, or location can be inferred from the input model. Additionally, the user must specify if conventional or HRV ventilation is to be used. For this study location was specified, and all buildings use HRVs.

Reference space heating systems can also be specified or inferred from the input model heating fuel. The three reference systems are natural gas and oil furnaces, and electric baseboards. Performance characteristics of these systems are taken as the minimums from Table 9.36.3.10 of the 2015 NBC. HOT2000 auto-sizes the furnace capacity, and uses the specified steady-state or annual fuel utilization efficiency (AFUE). Similarly, there are three reference domestic hot water (DHW) systems: electric, gas, and oil-fired conventional tanks. Tanks are assumed to be 50 gallons with performance characteristics equal to the minimums reported in Table 9.36.4.2 of the 2015 NBC. For this study, the reference HVAC and DHW systems were inferred from the system fuels in the input models.

New construction archetypes

Asaee and Ferguson (2019) developed the 240 new construction archetypes as a subset of the EnerGuide for New Housing Database (EGHD) (Blais et al., 2005). The EGHD currently contains records for over 1,000,0000 individual dwellings across Canada (Asaee et al., 2019). EGHD data is collected by energy advisers performing on-site audits of homes. Each audit contains over 162 information fields describing a home's "location, dimensions, building envelope insulation levels, type of windows and doors, type of heating and hot water systems and their energy efficiencies, energy analysis results, potential recommended upgrades, energy efficiency ratings and so on" (Blais et al., 2005). Asaee and Ferguson (2019) selected 15 single-detached and 15 double/row EGHD records for each of Canada's eight major housing markets. Selection criteria included no vintages earlier than 2015, and that archetypes must express the following range of dwelling characteristics:

- Number of stories (1-3);
- Conditioned floor areas (50-450 m^2);
- Window-to-wall ratio (0.05-0.35);
- Foundation type (basement, slab-on-grade, crawlspace);
- Ceiling/roof type (flat, attic).

The resulting set therefore expresses a broad range of built-forms drawn from actual contemporary dwellings being constructed across the country. Additional details are omitted for clarity, and the interested reader is directed to Asaee and Ferguson (2019) and Asaee et al. (2019).

Climate locations

Code-reference models were generated from all 240 archetypes in each of the following locations:

- Vancouver, BC (Climate Zone 4);
- Toronto, ON (Climate Zone 5);

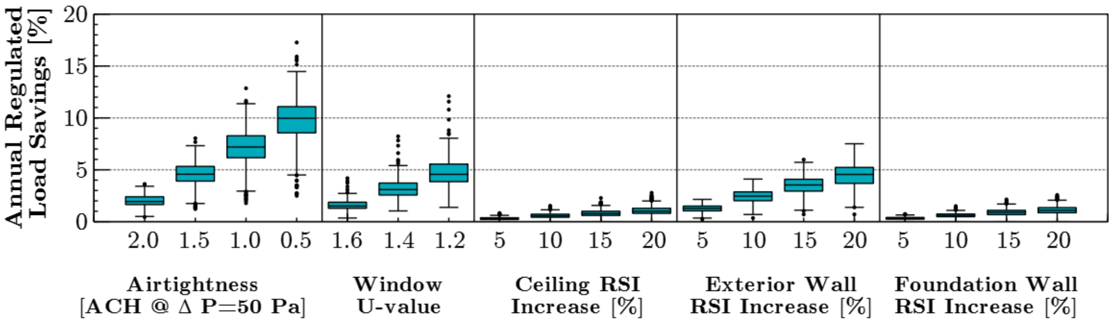

Figure 1: Archetype annual regulated load savings for ECMs in Climate Zone 4.

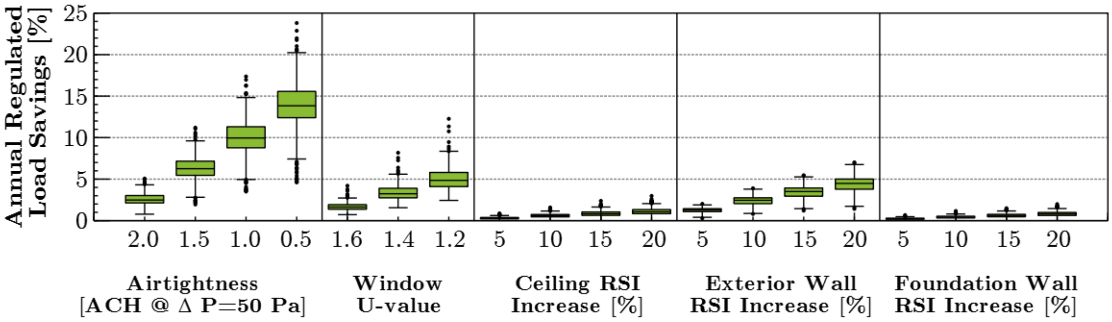

Figure 2: Archetype annual regulated load savings for ECMs in Climate Zone 5.

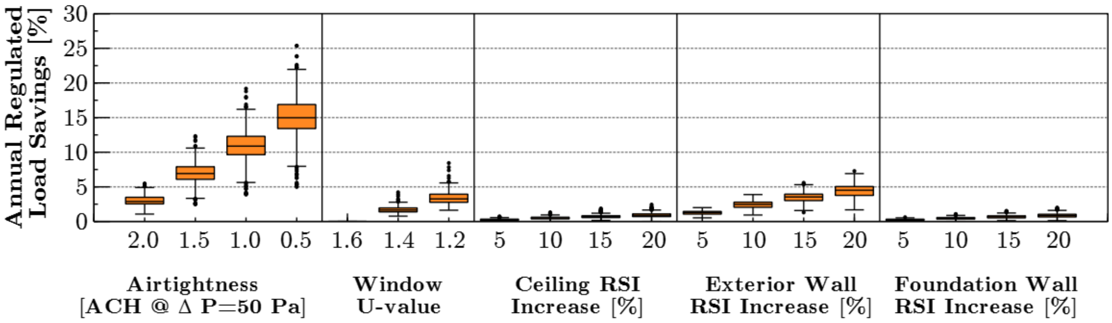

Figure 3: Archetype annual regulated load savings for ECMs in Climate Zone 6.

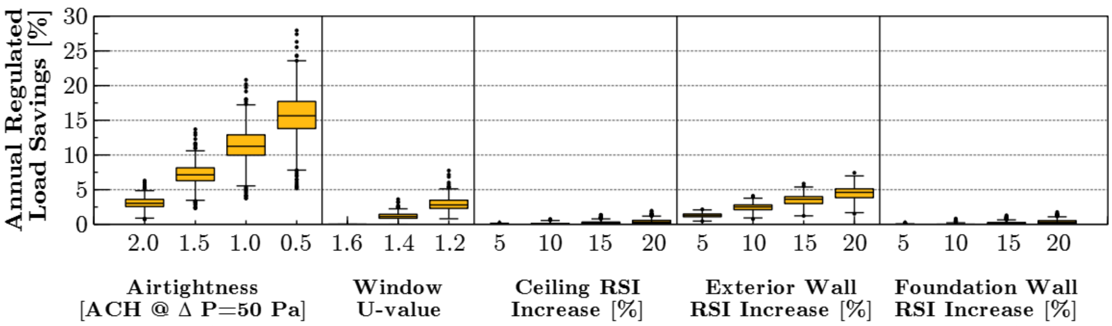

Figure 4: Archetype annual regulated load savings for ECMs in Climate Zone 7A.

- Montréal, QC (Climate Zone 6);
- Edmonton, AB (Climate Zone 7A);
- Whitehorse, YK (Climate Zone 7B);
- Yellowknife, NT (Climate Zone 8).

These locations represent the major 2019 housing markets in each Canadian climate zone (CMHC, 2019). In each climate zone, the rulset was used to set the corresponding minimum envelope performance parameters as dictated in Section 9.36 of the 2015 NBC.

Envelope energy conservation measures

For this study five envelope ECMs were considered: above and below-grade insulation, attic insulation, fenestration, and envelope airtightness. Opaque envelope component performance is modelled in HOT2000 using an effective R-value. For each climate loca-

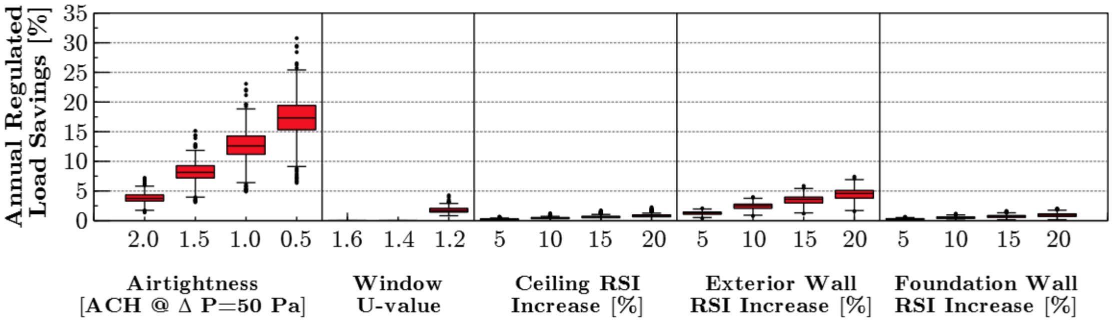

Figure 5: Archetype annual regulated load savings for ECMs in Climate Zone 7B.

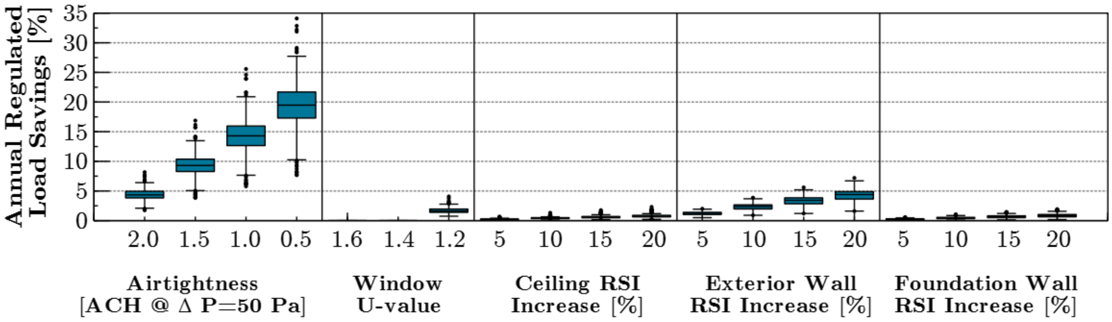

Figure 6: Archetype annual regulated load savings for ECMs in Climate Zone 8.

tion, the opaque envelope R-values were increased by 5%, 10%, 15%, and 20%. Fenestration is modelled in HOT2000 using system U-value and solar heat gain coefficient (SHGC). For all fenestration ECM and reference scenarios the SHGC was assumed to be 0.26 per sentence 9.36.5.14.(2b) of the NBC. For each climate location U-values were decreased by 0.2 W/m^2·K increments from code maximum down to 1.20 W/m^2·K. Only archetypes with basements were considered in the analysis for below-grade wall insulation (N=162). Similarly, only archetypes with attics were considered for the ceiling insulation ECM analysis (N=213).

Airtightness is modelled in HOT2000 using the Alberta Infiltration Model (AIM-2) (Walker and Wilson, 1990). This is an empirical model which characterizes infiltration flow using a power law expression and results from a fan depressurization test. The reference dwelling airtightness is 2.5 ACH @ ΔP=50 Pa, per sentence 9.36.5.14.(2d). For each climate archetype leakage at ΔP=50 Pa were reduced by 0.5 ACH to 0.5 ACH @ ΔP=50 Pa. This upper airtightness limit was informed by the Passive House Standard requirement of 0.6 ACH @ ΔP=50 Pa (PHI, 2015).

Performance indicators

Under the Section 9.36, performance path compliance is demonstrated by showing the proposed building consumes no more annual energy compared to the reference building. This annual energy calculation excludes lighting and plug loads, and is therefore referred to as the "regulated" load in this study. It has been proposed (CCBFC, 2020) that performance tiers in the code be specified as fixed percentage reduction of regulated loads between reference and proposed. Therefore, for this study the performance indicator for the ECMs is defined as percentage reduction in annual regulated load energy consumption relative to code-reference building.

Results

The distributions of archetype ECMs annual regulated load savings per climate zone are plotted in Figures 1 to 6. Across all climate zones improvements to exterior wall thermal resistance yields the greatest proportional nominal increase in performance compared to the other opaque component ECMs considered. Increasing ceiling insulation has historically been a cost effective way to increase envelope thermal resistance, however, Figures 1 to 6 suggest that further attic insulation increases yields diminishing returns. The energy savings are also likely overestimated since the model does not capture effects of eave compression along the roof edges. Increasing foundation wall insulation by 20% above code minimum is also shown in Figures 1 to 6 to achieve annual regulated load savings no greater than 3%.

For climate zones 4 and 5, upgrading from code-minimum 1.8 to 1.2 W/m^2·K fenestration nominally reduces regulated loads by 5%, with total variation in savings of 1% to 12%. In climate zones 6 and 7A, the minimum fenestration U-value is 1.6 W/m^2·K, and therefore that ECM does not achieve annual savings, shown in Figures 3 and 4. Similarly, the minimum fenestration U-value in climate zones 7B and 8 is 1.4

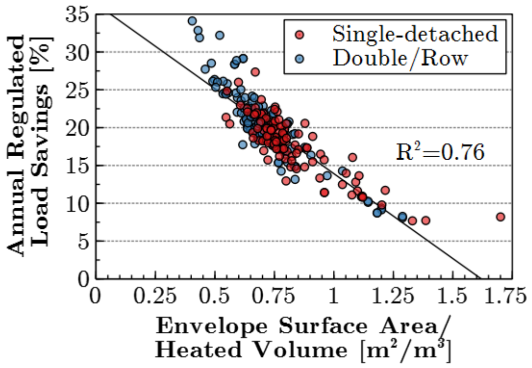

Figure 7: Variation of 0.5 ACH ECM efficacy with geometry for Climate Zone 8.

W/m^2·K, and therefore only the 1.2 W/m^2·K ECM is considered. For climate zones 4 to 7A upgrading fenestration to 1.2 W/m^2·K is shown in Figures 1 to 4 to have similar efficacy as increasing exterior insulation by 20% above code minimum.

The airtightness ECMs shown in Figures 1 to 6 have the greatest efficacy of all the ECMs considered for all climates. The nominal performance is also shown to increase with increasing climate zone. The variance of performance across different built-forms is also shown to be greater than the variance of the other ECMs. For example, in Climate Zone 8 reducing air leakage to 0.5 from 2.5 ACH @ ΔP=50 Pa achieves nominal 19% regulated load savings, with a total variation of 8% to 34%. The efficacy of airtightness ECMs were found to vary strongly with the ratio of envelope surface area to heated volume. Figure 7 plots this relationship for the 0.5 ACH ECM applied to archetypes modelled in Climate Zone 8; the coefficient of determination is 0.76.

Table 1: Climate Zone 5 nominal ECM regulated load and variation.

ECM	Mean Savings	Spread	CV
Airtightness @ ΔP=50 Pa			
2.0 ACH	2.6%	4.3%	0.31
1.5 ACH	6.2%	9.3%	0.27
1.0 ACH	9.9%	13.9%	0.26
0.5 ACH	13.6%	19.2%	0.25
20% Insulation Increase			
Ceiling	1.1%	3.0%	0.42
[1]AG Walls	4.4%	5.6%	0.22
[1]BG Walls	0.8%	2.0%	0.42
Fenestration U-value [W/m^2·K]			
1.60	1.7%	3.5%	0.30
1.40	3.4%	6.6%	0.30
1.20	5.1%	9.8%	0.30

[1]AG and BG are above and below grade

Table 1 provides the nominal and performance variance for the ECMs modelled in Climate Zone 5. As the airtightness and and fenestration ECM performance increases so does the spread of performance across archetypes. This was observed in all other climate zones, shown in Figures 1 to 6. Based upon the performance spread criteria, the most consistently performing ECMs are ceilings and foundation walls. Their corresponding nominal savings, however, are 1.1% and 0.8%, respectively. Accounting for nominal performance and performance spread using CV, above-grade walls and airtightness ECMs become the more desirable options since they have lower variance relative to their mean performance gains.

Table 2 provides the nominal and performance variance for the ECMs modelled in Climate Zone 8. The nominal energy savings achieved from airtightness ECMs is greater compared to Climate Zone 5, however, other envelope ECMs are shown to achieve similar savings to those in Table 1. This trend was found to be similar across all climate zones considered, thus they are omitted here for clarity.

Table 2: Climate Zone 8 nominal ECM regulated load and variation.

ECM	Mean Savings	Spread	CV
Airtightness @ ΔP=50 Pa			
2.0 ACH	4.4%	6.4%	0.25
1.5 ACH	9.3%	13.0%	0.24
1.0 ACH	14.2%	19.8%	0.24
0.5 ACH	19.3%	26.4%	0.24
20% Insulation Increase			
Ceiling	0.8%	2.3%	0.44
[1]AG Walls	4.3%	5.6%	0.23
[1]BG Walls	0.9%	1.85%	0.40
Fenestration U-value [W/m^2·K]			
1.20	1.7%	3.3%	0.29

[1]AG and BG are above and below grade

Discussion

Historically, prescriptive code changes have been evaluated using BPS and a single archetype (Proskiw, 2011a) or a smaller set of 11 archetypes (Proskiw, 2011b). These small sets of archetypes were useful in quantifying the benefits of potential code changes, but represented a limited view of built forms in practice. For example, none of the 11 archetypes used by Proskiw (2011b) contained flat roof surfaces whose thermal performance is regulated by the code. The EGHD, and derived subsets, can provide a richer database of actual built-forms from across Canada. This enables extended impact analyses that can begin to explore the uncertainty of performance for prospective code changes.

There is an interest to maintain prescriptive compliance paths in the building energy codes to simplify compliance checking for both builders and inspectors, as well as an interest in maintaining limited regulation on built form. Given these interests, large sets of archetypes and parallel computing tools like HTAP are useful for analyzing prescriptive code changes to ensure they broadly meet the overall energy savings goals in practice. Figures 1 to 6 illustrate that prescriptive ECMs efficacy can vary significantly, and the variation of ECM energy savings across built forms tends to increase with increasing nominal savings. The most consistently performing (per performance spread) ECMs found in this study are also those which achieve the lowest nominal performance. Shown in Table 1, they are the ceilings and below-grade wall insulation upgrades.

The alternative approach to quantifying nominal performance and consistency proposed in this work is the use of the CV metric. This metric normalizes standard deviation by data mean to assess the trade-off between nominal ECM performance and how much that performance varies across different envelopes. Based upon the data collected in this work airtightness and above-grade wall ECMs yield the most desirable CV values across all climate zones. They therefore provide the lowest performance spread across different built-forms with respect to the nominal performance. It is important to emphasize that the mean value used in the calculation of CV based upon the mean performance of the archetypes. The 240 archetypes were developed by Asaee and Ferguson (2019) such that they express a broad range of built-form characteristics; they do not represent the distribution of characteristics of contemporary new-builds since this data is unavailable. Therefore, in this analysis CV should be used as an indicator rather than an absolute performance quantity.

Conclusion

This study utilized 240 archetypes representative of contemporary new residential construction in Canada to simulate the efficacy of potential envelope building code performance requirement improvements. Increase code minimum ceiling and foundation wall insulation by up to 20% is shown to have limited annual savings. Therefore, the results suggest that further increases to these envelope component requirements will yield diminishing returns. Increasing exterior wall insulation by 20% is shown to nominally save approximately 5% across all climate zones, and therefore is a potential candidate for exploring additional energy savings through greater envelope insulation.

Bringing envelope airtightness from current code reference to Passive House standard levels was found to have the greatest nominal annual energy savings for all climate zones. Compared to all other ECMs considered in this study, however, it also has the greatest variance. In Climate Zone 8, for example, annual energy savings across the archetypes varied from 7.7% to 34.1% with nominal savings of 19.3%. Using the coefficient of variance (CV) as a metric of ECM nominal performance and variation, airtightness and above-grade walls are shown to be achieve the best trade-off of nominal performance and performance variation.

Future work

Future work will consider the robustness of packages of ECMs that are designed to achieve nominal tier performance targets. It is understood that energy transfer in buildings is complex, and buildings-as-a-system need to be considered to capture interactions between ECMs. For this analysis the min-max and minimax regret robustness indicators will be used. Robustness approaches are useful in analyzing consistency of performance across designs that are intended to achieve the same goal. This work presented the initial step in implementing robustness and uncertainty analysis into building energy codes research in Canada.

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