HVAC System Characterization for Enhanced Canadian Existing Buildings

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Abstract

Building archetypes are valuable for large-scale energy analysis, however there is limited granularity for older buildings. DOE Reference models classify them as either pre-1980 or 1980-2004. Furthermore, HVAC system replacement is not considered. This study addresses this by collecting system characteristic data for commercial and multi-unit residential buildings in ASHRAE CZ5, clusters them, and defines system inputs to support more granular archetype inputs. By presenting both the characterization and clustering methodology as well as the results, this paper supports improved energy simulation that better reflects the heterogeneity of the built environment, supporting more accurate urban energy modeling.

Introduction

Energy systems in buildings, such as Heating, Ventilation and Air Conditioning (HVAC), have been in place for more than a century and are useful in providing comfort and safety for people from harsh weather conditions, as well as proper air circulation for disease prevention. (Terranova, Cohen, and Fraser 1978). These systems have a significant impact on national and global energy consumption, as seen in the energy crisis of the 1970s. Almost 40% of the world's consumption of non-renewable energy sources takes place in the built environment, and about 50% of this energy flow is used for HVAC systems (International Energy Agency 2021; Vakiloroaya et al. 2014). Heating of building spaces constitutes 60% of total sector energy in Canada (NRCan 2021). This consumption impact significantly exacerbates the progression of the climate change crisis, and the large amount of energy used by HVAC systems becomes an even greater issue when a fault in HVAC systems result in a waste of energy. Thus, a robust building energy management strategy is necessary for the mitigation of the impacts of climate change.

One such practice is the development of retrofit energy conservation measures (ECM) developed by Building Energy Models (BEM). As suggested by the name, BEMs are mathematical models of the energy consumption of a building or group of buildings. BEMs are used as a tool during the early design stage for assessing the cost effectiveness of different energy system designs, during operational stages for assessing various performance optimization measures and predicting energy consumption in buildings over a period of time (Jacobs and Henderson 2002; Hygh et al. 2012). There has been a great deal of research within the Building Information Modeling (BIM) field about BEMs as a retrofit Energy Conservation Methods (ECMs) evaluation, as retrofitting buildings with better energy systems can increase energy efficiency and reduce energy consumption (Pan et al. 2023; Huang and Brodrick 2000).

BEMs typically rely on building archetypes, which are building samples that represent a subset of building stock with similar characteristics. In Canada, these archetypes are classified under Building Technology Assessment Platform (BTAP), a categorization database developed by the Natural Resources Canada (NRCan) organization. These archetypes are built upon the US Department of Energy (DOE) Building Stock (Deru et al. 2011) and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standards 90.1-2004 and Standard 62.1-2004 b (ASHRAE 1989; ASHRAE 1999, ASHRAE 2013). One major issue with the BTAP archetypes database is the categorization granularity; it is a simplistic sentiment to assume that buildings made before 1981 are largely similar in terms of HVAC systems, building envelope, materials, occupancy use and other building parameters. This simplified assumption makes no considerations made towards the evolution of HVAC systems and equipment over time in pre-1981 buildings or the impacts of said evolutions, and results in the development of low accuracy energy models. A higher granularity of archetypes is required in order to develop models with higher granularity that can assist in the implementation of proper retrofit measures for each building.

The objective of this research study is to increase the granularity of existing building archetypes in order for future retrofit ECMs to be implemented properly. In order to achieve this, this paper explores the brief history of

building archetype development in North America and discusses the methodology used in this study to characterize building archetypes in the city of Toronto. Developing archetypes with a higher level of granularity is important in the context of implementing retrofit ECMs in Toronto as it would allow for more robust and accurate building simulation models of the city's building stock, and thus, more opportunities for smarter retrofitting projects. This research aims to address the growing urgency of climate change, particularly evident in the shift of Southern Ontario from Climate Zone 6 to Climate Zone 5 according to the ASHRAE standards (ASHRAE 2020).

Background

There have been several studies that deal with the development and categorization of building archetypes. One of the most notable has been Huang et al. (1991), which aimed to model the energy use in existing commercial building stock as closely as reasonable for market analysis of cogeneration systems. The building parameters for classification were selected based on the best potential to use cogeneration. It presented a collection of building characterizations and databases for energy simulations, and sourced data from the Commercial Buildings Energy Consumption Survey (CBECS). It developed 481 prototypical commercial buildings from 37 building types and 13 locations.

The archetype characterization from Huang et al. (1991) was improved upon in Huang and Franconi (1999), using 120 prototypical buildings covering 12 building types of old and new construction. They set out to simulate the heating and cooling loads of various building components in existing commercial buildings and did so with marginal success. Stocki et al. (2005) based their methodology on Huang and Franconi (1999) to establish standardized assumptions for commercial building energy analyses. It defined seven building types made to mirror typical commercial buildings, however there was very little justification for the groupings. The results of this study became the basis for ASHRAE Standards 90.1-2004 and Standard 62.1-2004 b (ASHRAE and ANSI 2006; ASHRAE and ANSI 2007).

These prior studies served as the foundation for two major studies done by the National Resource Energy Laboratory (NREL); US DOE Stock Characterization Study (Deru et al. 2011) and U.S. Building Stock Characterization Study: A National Typology for Decarbonizing U.S. Buildings (Reyna et al. 2021). Deru et al. (2011) explored the development of standards and reference energy models for the most common commercial buildings and developed as starting points for measuring energy efficiency goals in commercial buildings. It characterized about 70% of the commercial building stock in the United States, and the models are fully defined in the spreadsheet scorecards of EnergyPlus input files. The study selected a small number of prevalent building types and developed weighting factors to represent a percentage of the commercial building stock. A set of 15 commercial building types represents 3,279 buildings (of 5,215) from the full Commercial Buildings Energy Consumption Survey CBECS dataset. Buildings in this study were classified by Principal Building Activity (PBA).

This led to (Reyna et al. 2021), a further NREL study on US Building Stock Characterization. The focus of this study was U.S. building typology segments focused on deep energy retrofits in the effort to target a zero-carbon building stock. Segmentation of the stock was based on commonly available characteristics; vintage, number of units, building type and climate zone.

Presently, building archetype utilized in BEMs follows. Urban BEMs or UBEMs are models that analyze performance of a group of buildings in the urban context, to show the energy use dynamics within individual buildings, inter-building effects and urban microclimate (Hong et al. 2020; Johari et al. 2020). The typical process of UBEM development is as follows; data collection, classification or segmentation of the building stock based on building typology/functionality, characterization by two methods; deterministic and probabilistic and model calibration (Cerezo et al. 2017; Pasichnyi, Wallin, and Kordas 2019).

A novel UBEM case study was performed in Sokol, Cerezo Davila, and Reinhart (2017), where a more detailed methodology was employed while faced with incomplete information about the buildings was explored. It was a case study for buildings in a neighborhood in Cambridge, Massachusetts. The data collected included building geometry, building properties, weather data and measured energy consumption from HVAC systems. The classification approach used was probabilistic, based on available data such as prior literature, historical building data and energy databases (Sokol, Cerezo Davila, and Reinhart 2017).

Characterization for this study was mixed; deterministic for known parameters and probabilistic for parameters with high uncertainty. Calibration used was the Bayesian method, a mathematical iterative process of updating uncertainty distributions on model parameters consistently with known data points. This process determines the most likely uncertainties for input parameters that yield an output uncertainty in which the known data is most feasible (Muehleisen and Bergerson 2016). The results of this study showed that employing the probabilistic method led to more accurate distributions of building energy use in the district.

Methodology

This study was executed in three stages: data collection, building segmentation, and characterization. These were undertaken as described in the sections below.

Data Collection

Due to the low accessibility to discrete energy and HVAC component information, the data was collected from a historical survey of HVAC systems in North America from 1850 to 2004, EnergyPlus reference models from the US DOE and the Energy Code section of the National Building Codes (NBC) of Canada. Several hundred energy models were reviewed by an industry partner, as existing energy models could not be shared directly due to privacy concerns. The criteria for data selection were the energy models readily available for analysis, and parameters were extracted from these models.

Building Segmentation

For this study, the buildings were classified using deterministic methods, whereby buildings are classified according to their 'theoretical energy' use determined by specific known parameters (Johari et al. 2020). The parameters chosen for this study are the period built and building typology or function. Existing buildings are classified as any building constructed prior to 2004.

Characterization Methodology

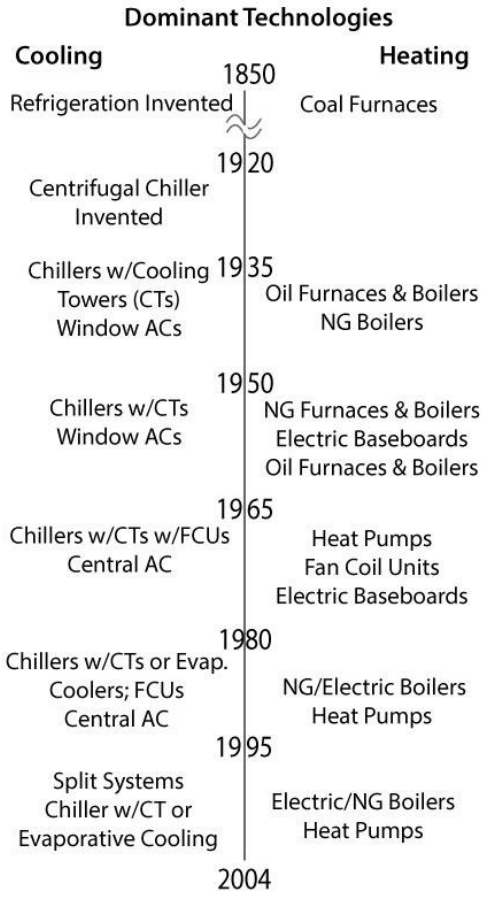
The characterization method used in this study is a combination of deterministic and probabilistic; due to the unavailability of certain energy use data for Toronto, a deterministic approach was utilized. However, with known data, such as the availability of Variable Air Volume (VAV) air handling unit (AHU) systems versus the availability of Constant Air Volume (CAV) systems were characterized probabilistically. Since 70% of AHU systems are known to use VAV, it is assumed the default for any encountered AHU systems. Applying these methods to the data collected from earlier, the building types were categorized based on HVAC system type and energy efficiency rating.

Results

The building stock was segmented functionally into commercial buildings and multi-unit residential buildings (MURBs) according to ASHRAE 90.1-2004. A commercial building is classified as any office building, and an MURB is classified as a building with two or more dwelling units (ASHRAE 1999).

Figure 1 shows the timeline of the HVAC system development in North America. While heating systems have been around since the early 1800's, cooling systems were not mainstream until 1935 when they were sold commercially in North America. The HVAC system timeline was sourced from records of the Department of Energy from the United States, as the similarities between the United States and Canada where Climate Zone 5 are shared are high (Lester 2015). Moreover, the standards of HVAC Systems in Canada currently follow the recommendations of the United States DOE's Uniform Test Method for Measuring the Energy Consumption of Central Air Conditioners and Heat Pumps (US Department Of Energy 2017).

Fig 1: Evolution of HVAC Systems Over Time (Lester 2015; US Department Of Energy 2017)



Classification

Prior to classification, a history of HVAC technology development was undertaken, identifying key inventions as well as the most dominant systems over time. Figure 1 shows these by 10-to-15-year intervals, as this was the rate of advances in HVAC technology (Lester 2015). One thing to note is that most HVAC equipment have 15-to 25-year lifespans (Conditioned Air Corporation 2018). This means that it is safe to assume that major equipment (boiler, chiller, cooling tower) efficiencies of current equipment in Canada are no worse than those prescribed by the Model National Energy Code for Buildings (MNECB) 1997.

This figure shows that a majority of older building stock (pre-1980) are expected to use gas and /or electric boilers and furnaces for heating, and chillers and air conditioning for cooling, while more recent existing buildings use heat pumps, variable air valves and boilers for heating and almost all forms of cooling systems. This follows recent

trends towards retrofitting older buildings. An important consideration for characterization is that most pre-1935 buildings do not have the infrastructure for larger cooling systems to be installed, so the assumption can be made that their only cooling system is open windows.

HVAC Characterization Based on Building Typology

For HVAC characterization based on building typology, the classification is sourced from ASHRAE 90.1-2004 standards for commercial buildings (ASHRAE and ANSI 2006). Table 1 details the characterization and further shows the demarcation between HVAC systems on functionality. It gives typological context to the periodic categorizations from earlier. For instance, a hotel built in 1985 would use a different cooling system from a large office built in the same period, due to the functional requirements of each. Retail buildings are always assumed to have rooftop units attached. This context becomes especially important with hospitals as their HVAC systems are regulated under specific regulations such as CAN/CSA-Z317.2 (Natural Resources Canada 1997; Natural Resources Canada 2011).

Table 1: HVAC Characterization Based on Commercial Typology Classification (ASHRAE and ANSI 2006)

Building	**HVAC Systems**
Mid-Rise Apartment	Split system units; Exchanger (DX) cooling and gas furnace
Hospital	Water cooled electric chiller, natural gas boiler, 2 Varied Air Valve (VAV) and 2 Constant Air Valve (CAV) systems
Large Hotel	2 air-cooled electric chillers, natural gas boiler, CAV, electric unit heater
Large Office	2 water-cooled chillers, VAV with reheat and plenum zones
Medium Office	Packaged Single Zone Air Conditioner (PSZ) with plenum zones, gas furnace
Outpatient	DX cooling, natural gas boiler, 2 VAV systems with reheat
Primary School	Packaged VAV with hot water re/heat; PSZ-AC and gas furnace
Quick Service Restaurant	PSZ-AC, gas furnace
Secondary School	Packaged DX, boiler, Multizone (MZ)-CAV with reheat; PSZ-AC and gas furnace
Full-Service Restaurant	PSZ-AC, gas furnace
Small Hotel	PTAC, Electric unit heaters
Small Office	PSZ-AC, gas furnace
Stand-Alone Retail	PSZ-AC, gas furnace; electric unit heater
Strip Mall	PSZ-AC, gas furnace
Supermarket	PSZ-AC, gas furnace
Warehouse	PSZ-AC with gas furnace

Equipment Efficiencies

The codes in NBC do not specify required efficiencies for HVAC systems until 1997 under the National Energy Code for Buildings (NECB) under 5.2.13 in the 1997 edition (Canadian CBFC, Natural Resources Canada, and Government of Canada 1997) and Division B Part 5 in the 2011 edition (Canadian CBFC, Natural Resources Canada, and Government of Canada 2011). Prior to that time, the codes only went into detail on measurement specifications within buildings (ASHRAE and ANSI 2006).

Prior to 2000, natural gas boilers with higher than 80% fuel conversion efficiency were rare. In addition, the design standard to minimize the size and cost of heating terminal devices (baseboard convectors, fan coils, etc.) was to supply water at 180°F (82°C) and return at 160°F (71°C). From 2000 onwards, mid and high efficiency (83 to 87%) became more popular, and some existing buildings designed for high temperature distribution could be converted to these natural gas boilers. Gas fired rooftop equipment has a maximum of 80% fuel conversion efficiency. The reason is figuring out the placement of the flue gas condensate. Draining the condensate on the roof during winter means creating a frozen lake on the roof. A solution is engineered Air Rooftop Units where the condensate is drained inside the roof curb into the building (within heated space), but this is very rare.

The change in focus on HVAC efficiency is most likely due to the energy crisis of the early 1970's, where a greater emphasis on energy efficiency in buildings was placed. It is safe to assume that the minimum efficiencies stated in the codes past 1980 for HVAC systems were typical of most buildings in the region in that time period. Also, regulations typically lag considerably behind standards by a few years, so an assumption can be made that the NECB codes of 1997 and 2011 can be applied to 1980-1995 and 1995-2004 respectively.

Figure 2 shows a sample of the pattern of efficiencies from heating systems from these periods. Figure 3 shows a sample of the pattern of performance values from cooling systems from both periods

Fig 2: Evolution of Typical Heating Efficiencies Over Different Periods (Natural Resources Canada 1997;

Natural Resources Canada 2011)

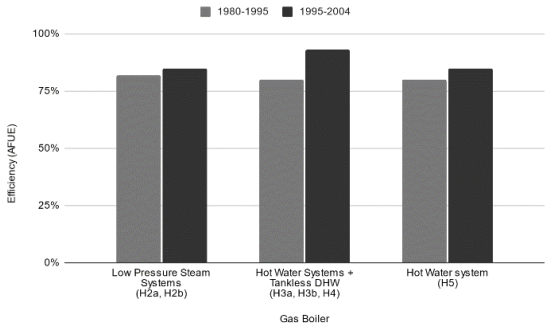
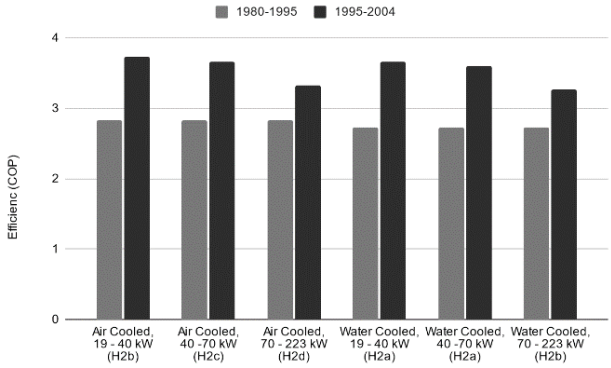


Fig 3: Evolution of Typical Cooling Equipment Performance Over Different Periods(Natural Resources Canada 1997; Natural Resources Canada 2011)



As shown in both figures 2 and 3, it is clear that the push towards increased energy efficiency starting in 1995, made significant changes in overall system efficiency. The ASHRAE 90.1 energy efficiency standard was first adopted by many regions in North America at that time. Moreover, energy trends from 1990 to 1995 showed a significant increase in energy consumption from the commercial sector, thus making the increase in efficiency regulations necessary (National Resources Canada [1995] 1997). The expectation then with building stock categorization is that systems placed in buildings before 1995 have lower efficiency ratings than their later counterparts.

Building Clustering Summary

From this analysis, five major clusters were developed based on the following systems:

Rooftop Package and DX cooling, Gas fired Recirculating Multizone, Non-condensing Forced Air Convection, Condensing Boiler with Recirculating Multizone and Fan Coil Unit, and Condensing Boiler with Corridor and Kitchen Pressurization. They can be broken down into sub clusters based on the categorizations of period, typology, equipment life span and equipment efficiency. Table 2 displays this information in detail.

H1 captures smaller commercia buildings, where it is expected that they would use a Rooftop Package and DX cooling system. H2 captures a large number of mid-size commercial buildings and all large size commercial buildings. It is split into four subclusters; H2a, which captures non-condensing natural gas boilers with and hydronic heating, H2b, which captures oil boiler with hydronic heating and H2c and H2d which captures Multizone recirculating systems. H2a and H2b are likely to be found in mid-size buildings built before 1960's while H2c can be found in post 1960 mid-size and H2d is found in large commercial buildings. H3 all small MURBs and is split into two subclusters; H3a, which captures those that don't use window ACs and H3b, which captures those that use window ACs. H4 captures mid-rise MURBs with Non-condensing NG boiler with hydronic heating and window ACs. H5 captures mid and high rise MURBs that utilize non-condensing boilers with Fan Coil Units.

Mid-size commercial buildings are more likely to have a VAV system, though there is a minority of these buildings that operate with CAV systems. However, with the implementation of HVAC retrofits, the assumption is that the default will be a VAV system since most CAVs are currently out of compliance and will need to be updated. All MURBs are expected to utilize some form of Non-condensing boiler for heating Small MURBs either have non-existent cooling if built before 1970 due to cost of installation, or occupant installed window shakers or ACs post 1970. Mid and High rise MURBs will be expected to use air or water chillers depending on size.

Table 2: HVAC Clusters based on Classification and Characterization Methods

Cluster #	Bldg. Type(s)	Period(s)	Modeled System Type	Efficiency (%)	Efficiency (COP)	Mechanical Ventilation	Expected Life	Other Comments
H1	Smaller commercial (1-3 stories)	1960-2004	Packaged gas-fired & DX cooling rooftop unit	Heating: 75 Cooling:	Heating: Cooling:	Assumed none (operable windows)	15-20 yrs.	Likely replacement @ end-of-life

H2a	Midsize commercial	pre-1960	Non-condensing NG boiler with hydronic heating, Water Cooled Chiller Tower w/ FCU	Heating: 75 Cooling: -	Heating: - Cooling: 4.5	None	20 yrs. for the boiler	Assume retrofit with MNECB 1997 efficiency non-condensing boiler
H2b			Non-condensing NG boiler with hydronic heating	Heating: 75 Cooling: N/A	Heating: - Cooling: -		20 yrs. for the boiler	
H2c	Mid-size commercial	1960-2004	Multizone recirculating system w/gas-fired (rooftop) AHU; Water Cooled Chiller	Heating: 80 Cooling: -	Heating: - Cooling: 2.8	Multi-zone recirculating AHU w/CAV	Boiler 20 yrs. max; AHU 25+ yrs.; chiller 15-20 yrs.	Approximately 30% of buildings are still CAV; 70% VAV. Assume boiler & chiller retrofit with MNECB 1997 Efficiency
H2d	Large commercial	1960-2004	Multizone recirculating system w/gas-fired (rooftop) AHU; Air Cooled Chiller	Heating: 80 Cooling: -	Heating: - Cooling: 4.5	Multi-zone recirculating AHU w/VAV	boiler 20 yrs. max; AHU 25+ yrs. Chiller 20-30 yrs.	Approximately 30% of buildings are still CAV; 70% VAV. Assume boiler & chiller retrofit with MNECB 1997 Efficiency
H3a	Small MURBs	pre-1970	Non-condensing NG boiler with hydronic heating	Heating: 75 Cooling: N/A	Heating: - Cooling: -	None	Boiler 20 yrs.	Assume retrofit with MNECB 1997 efficiency non-condensing gas boiler; reluctant to upgrade to FCUs because of lost
H3b	Small MURBS	pre-1970s	Non-condensing NG boiler with hydronic heating and window ACs	Heating: 75 Cooling: -	Heating: - Cooling: 3.16		20 yrs. for the boiler; 10 yrs. for window AC	
H4	Mid-Rise MURBS	post-1970	Non-condensing NG boiler with hydronic heating and window ACs	Heating: 80 Cooling: -		Corridor Pressurization + Kitchen/ Bathroom exhaust	20 yrs. for the boiler; 10 yrs. for window AC	
H5	Mid-Rise & high-rise MURBS	1980-2000	Condensing boilers, Chiller system w/FCUs	Heating: 80 Cooling: -	Heating: Cooling: 4.45	Corridor Pressurization + Kitchen/ Bathroom exhaust	20 yrs. for the boiler; 20-30 yrs. for Chiller	Assume retrofit with ASHRAE 2004 units and thus use current BTAP systems

Conclusion

Through analysis of historical, regulatory and modelling data, this paper found that the Toronto building stock can be grouped into five major clusters based on HVAC system type characterizations. These five clusters can further be broken down into nine groups based on building typology characterization. This is a significant improvement to the original groupings covered by the BTAP system, and brings the total from two to ten. Further study into the characterizations of Toronto building stock is required for higher fidelity of archetype granularity. Recommendations for such future studies include gathering more specific energy data sources from the city for more deterministic categorization, the utilization of unsupervised clustering techniques and the use of model development and calibration.

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