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CITYRETROFIT: DEVELOPMENT OF A DISTRICT-SCALE DIGITAL TWIN

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Abstract

CityRetrofit integrates publicly available datasets with building archetypes to create urban building energy models (UBEMs). The tool integrates geospatial data, occupancy schedules, construction assemblies, and HVAC/energy system characteristics for both baseline and potential retrofit scenarios to support retrofit strategy development at the urban scale. This paper summarizes the development of this workflow in a mandatory building energy disclosure context (Montreal) and its extension to a jurisdiction without such disclosure (Toronto). The resultant case study demonstrates the workflow. The results show CityRetrofit's adaptability across jurisdictions to inform urban decarbonization policy.

Introduction

Global cities face mounting pressure to reduce CO_2 emissions but the sheer scale of retrofits is overwhelming, particularly given the paucity of building energy disclosure in many jurisdictions, existing building heterogeneity, and the lack of appropriate simulation tools.

Previous work has explored various approaches to urban building energy modeling (UBEM) , most notably single- and multi-zone bottom up simulation and top-down energy mapping. While the latter was enabled with mandatory building energy disclosure (MBED) laws, the ability to simulate building system performance was necessary to model and evaluate potential retrofit pathways. In this context, bottom-up models play a critical role.

Urban Building Energy Modeling (UBEM) tools have been developed to analyze city-scale energy flows, with a strong focus on building stocks and their interactions within the urban context, such as shading, thermal exchanges, urban heat island effects, and vegetation (Allegrini et al. 2015).Over time, a wide range of tools have emerged, using different modeling approaches—from reduced-order and resistance–capacitance models to detailed dynamic simulations—and varying in scope, input formats, and integrated features like transportation, life-cycle analysis, or cost–benefit assessment .

Despite these advances, the literature shows that existing Urban Building Energy Modeling (UBEM) tools have progressively improved the representation of urban energy flows—particularly building stocks and their interactions—using a wide range of modeling approaches and simulation engines (Monien et al. 2017). However, most tools remain strongly conditioned by the specific use cases for which they were originally developed, leading to limited modularity, scalability, data flexibility, cross-sector integration, and automation, as well as difficulties in clearly communicating results.

To address these gaps, recent research argues for moving away from tool-specific, ad hoc solutions toward an open-source, flexible framework built around a central urban data model capable of handling heterogeneous data sources and interfacing with multiple simulation tools at different levels of detail. This approach aims to support diverse urban sustainability and building retrofit use cases by integrating different processes and software within a unified, adaptable structure rather than relying on a single modeling engine, following (Gavaldà-Torrellas et al. 2025).

To populate such workflows, archetype development has been a topic of significant research globally. In the North American context, two sets of archetype libraries were available: 'reference models' for older (pre-2001) buildings, and 'prototypical' code-minimum models aligning with each version of the ASHRAE 90.1 energy efficiency standard, which was released codified on a three-year basis. This has been adapted regionally, for example the Canadian Building Technology Assessment Platform (BTAP) (CanMet Energy, 2023) that adapt these to local codes. The latter was a reasonable approximation for newer building stock, since this standard has been codified into regional codes across North America.

The former reference models (US DOE, 2012), however, categorize older buildings into two broad vintages: pre-1980 and 1980-2004, regardless of building type or form. This simplification fails to capture critical differences in construction practices, materials, and code requirements within each period. As a result, these archetypes often misrepresent the performance of older buildings, leading to inaccurate energy predictions (Li & Feng, 2025). The development and integration of more granular characterizations was thus critical to capture these differences.

Within Europe, there has been substantial archetype development, using both bottom-up and top-down aggregation methods; see (Mata, Kalagasidis, & Johnsson, 2014) for a comprehensive review. Across multi-country studies, the use of code minimum performance has been shown to consistently estimate building stock performance with low (<5%) error (Mata et al., 2014).

This paper presents the development of the CityRetrofit tool for Montreal, its supporting workflows, and its extension to incorporate bottom-up approaches allowing its mapping to new jurisdictions with significantly limited public data. A case study for Toronto, a cold climate (ASHRAE Climate Zone 5 (CZ5)) dense urban context was presented to demonstrate and validate this process. The resultant tool supports its adaptation and replication, providing a scalable digital twin suitable for decarbonization policy and district energy planning across global urban contexts.

The paper was structured as-follows. First, the methodology guiding the development of CityRetrofit was presented, including geometric data processing, energy model input mapping, and the detailed development of refined inputs (to address the above oversimplification limitations) to provide more accurate baseline and retrofit pathway building-level models for UBEM integration. Next, the resultant inputs were summarized, and the platform integration was presented. Finally, the extension to other jurisdictions was discussed and the future research trajectory to address current limitations was presented.

Methodology

The CityRetrofit platform was developed through four overlapping phases: (1) workflow development; (2) ingestion of building geometry; (3) building archetype refinement; (4) retrofit design and analysis; and (5) integration and testing using a second urban area (Toronto) as a use case.

Workflow development

Existing UBEMs rely on use-case–specific architectures and back-end simulation engines, which constrains modularity and limits their computational scalability when extended to large building stocks, multiple cities, or cross-sectoral applications, as evidenced by their typically small-scale deployments in prior studies. In line with previous benchmarking research, the limited automation of data ingestion and preprocessing remains a key bottleneck, increasing human effort, reducing reproducibility, and hindering systematic comparison across tools and case studies. Moreover, the trade-off between reduced-order and detailed dynamic simulation approaches restricts their suitability for different decision contexts, ranging from rapid policy screening to high-resolution retrofit analysis. The proposed CityRetrofit platform addresses these gaps through an open-source, centralized data model that automates data handling, enables transparent benchmarking across simulation engines, and supports scalable, decision-relevant outputs tailored to policymakers, urban planners, and researchers. From a detailed perspective, the CityRetrofit platform integrates empirical data, archetype-based modeling, simulation, and comparative assessment to support scalable, portfolio-level retrofit decision-making through five main stages: (1) Building energy demand calculations, including geometric data acquisition and preprocessing, construction and usage archetype assignment, and weather file selection; (2) HVAC system assignment and energy disaggregation; (3) Retrofit identification and characterization; (4) Retrofit assessment; and (5) Visualization (Fig. 1). This modular structure enables scalability and adaptation to different building stocks and jurisdictions.

Building-level data availability determines the modeling approach adopted. For bottom-up analyses, geometric information is required and can be extracted from CityGML, 3DS, or GeoJSON files at varying levels of detail (LOD1/LOD2), all of which were processed through a unified geometry factory. When detailed geometry is unavailable, predefined geometrical archetypes enriched with building attributes were employed instead. These archetypes were developed by clustering extensive geometric and monthly energy datasets from data-rich cities, resulting in a set of transferable, high-resolution building representations integrated into the tool.

Building geometry ingestion

The first step for building modeling was the creation of a 3D city model. This model can be generated from multiple

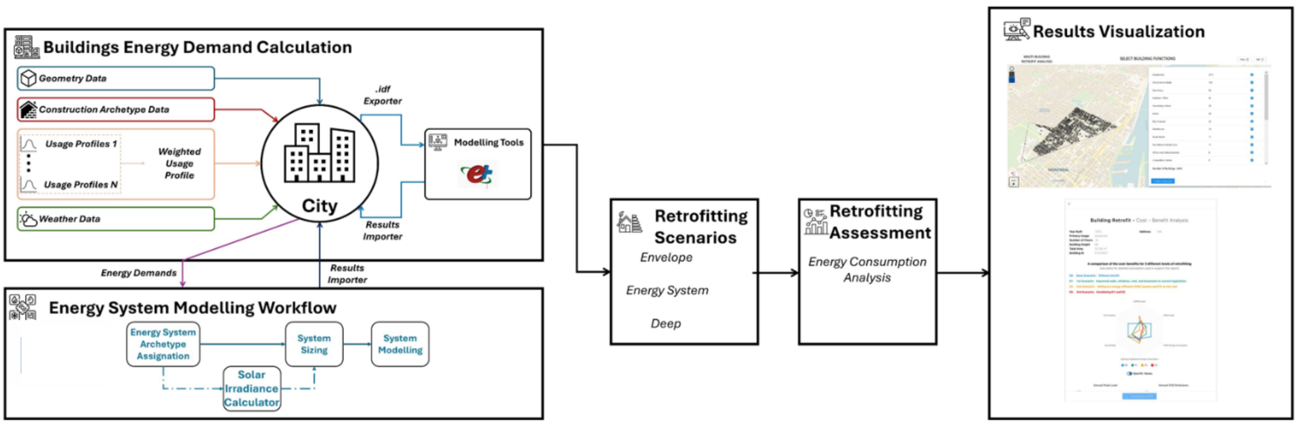

Figure 1: CityRetrofit workflow

formats, including GeoJSON, obj, 3ds and CityGML. Automated processes to validate and integrate different data sources was developed. For Québec cities, the input data was created by combining several open-source datasets including LiDAR aerial data (Montréal 2026a), property assessments (Montreal 2026a), Building Footprints (Canada 2026), and Layer 2 cadastral data for disaggregated building use types (Université Laval 2026). A validation and cleaning process, comparing the results with sources of ground truth (utility data for 2019-2021 divided by building function and Forward Sortation Area) was developed and helps validate the process of merging initial low-quality datasets, which was a usual situation in large scale city data. The comparison between simulated and measured energy use showed good agreement, with deviations generally within 15–20%, consistent with previous validation studies of the proposed UBEM workflow (Gavaldà-Torrellas, Monsalvete, Ranjbar, & Eicker, 2025).

Required building inputs include year of construction, building function, and height. The process begins by creating an instance of the *City* class, which was then populated with city object information extracted from the input file through a dedicated importer. This importer enriches the city model by integrating both geometric and attribute data. Once the city objects were extruded to form a 3D representation, the internal zoning of buildings was defined. At present, each building is modeled as a single thermal zone, although several multi-zoning approaches are currently under development. An important aspect of the approach taken was the capacity of ingesting different levels of detail of data (presently LOD1 and LOD2) depending on the quality of the original data sources.

Archetype development

Non-geometric building attributes were captured using archetypal constructions, systems, and scheduled, to map to the geometric archetypes. Existing reference and prototypical building models – e.g. DOE/ASHRAE and BTAP reference and prototype models – were used to provide the starting point for archetype development, providing reference geometry, construction assemblies, HVAC system definitions, and building schedules by period and type. A review of these archetypes against the existing building stock indicated a need for more granular construction and HVAC system characterization for the pre-2001 commercial (office) and multi-unit residential (MURB) building typologies while smaller buildings were more consistent with respect to both construction and HVAC systems. In all cases, occupancy schedules follow ASHRAE 90.1 as these were typical across the building stock.

Archetype development in a mandatory building energy disclosure context

Because Montreal had publicly available building energy use, that data was used to validate and refine inputs from the literature and allowed building clustering similar to what was achieved for the geometry.

Construction archetypes

Construction assemblies were re-evaluated through recalculation of U-values using explicit material properties and consistent assumptions regarding layer composition and air gaps. This process led to improved representation of post-2000 lightweight cladding systems, correction of legacy U-values where discrepancies were identified, and harmonized treatment of air gaps in accordance with building physics best practices. In parallel, the material library was expanded to include underrepresented but commonly used materials, such as stucco finishes and explicit air-gap layers, improving transparency and physical realism. Terminology was standardized across archetypes to ensure consistency with BTAP, NECB, and ASHRAE conventions, facilitating interoperability and collaboration.

To enable a robust and comparable assessment of building energy performance, this study applies a set of statistical diagnostic methods to both measured utility data and simulated baseline consumption. The primary analytical framework was the PRISM (PRInceton Scorekeeping Method), which characterizes the relationship between energy use and outdoor air temperature through segmented linear regression, yielding key indicators such as heating sensitivity (Fig 2).

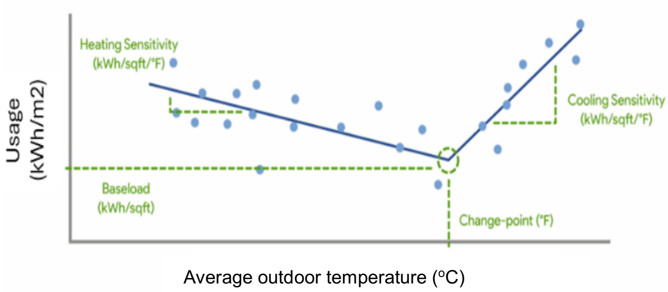

Figure 2: PRISM methodology

At the portfolio scale, kernel density estimation (KDE) was used to identify a reference centroid representing typical thermal performance within the building stock, allowing individual buildings to be benchmarked relative to representative baselines rather than absolute thresholds.

HVAC/Energy system archetypes and data model

In addition to construction and usage archetypes, each building must have the HVAC system assigned, which permits energy disaggregation. This process was done automatically where the assignation criteria can be defined based on: (1) Regional statistics; (2) Current building codes (for retrofit performance requirements); and (3) Scientific literature.

Process automation was enabled through the development of a generic object-oriented energy system data model where all the energy system-related data needed in simulation and optimization were structured in a parametric, generic, and extensible way. This provides a structured, object-oriented representation of building energy systems that explicitly separates data representation from simulation and optimization logic.

All system components – namely generation, storage, distribution, and emitters – were described through standardized classes with well-defined attributes, relationships, performance curves, and cost functions.

This separation enables the same data structures to be reused consistently across feasibility screening, hourly simulation, life-cycle costing, and multi-objective optimization, without rewriting model logic for each application. The object-oriented design supports modularity and extensibility: new technologies or manufacturer-specific components can be introduced by adding data entries or subclasses, without modifying the computational workflow. As a result, the data model serves as a robust computational backbone that enables scalable automation, cross-climate comparability, and relevant system analysis, while remaining compatible with semantic annotation or ontological layers if broader interoperability was required in future extensions. The appropriate energy system archetype was assigned. The system component parameters were retrieved from the energy system data and passed on to the simulation model. System retrofit analysis is implemented by changing the energy system archetype from that of the base case.

Extension to the low data availability context

Because of the lack of publicly available building energy data in Toronto, a more empirical approach was necessary to refine archetypes. Buildings types for CZ5 were characterized and clustered according to construction assemblies and HVAC systems to enrich existing building archetypes to reflect the full range of variations in form, use, and system configurations. This was done in three key phases: (1) historical analysis; (2) relevant code review; and (3) validation.

The construction historical analysis was based on an architectural study, which characterized the various forms, window-wall-ratios (WWRs), and constructions associated with each of the 20th century architectural movements. These movements were broadly used to define building styles and tend to be international in scope, providing a broadly-applicable method for building classification. Each architectural movement period was mapped to identify periods where multiple distinct styles were present within a single period. This approach allowed the archetypes to capture the diversity of common building types across typologies and identify the defining characteristics for each. The HVAC historical analysis similarly looked at the invention and period of adoption for various equipment and system types, grounded in industry documentation and previous historical studies (Carrier 2012, US DOE 2015).

While the historical analysis provided insight on typical equipment and construction types, these did not provide sufficient detail to model the performance of the HVAC /energy systems and construction assemblies. For this, a detailed code review was undertaken, where the various iterations of relevant building and energy codes were reviewed and prescribed performance was documented at each point. Once this was complete, periods with different code mandated-performance were used to subdivide the building sets and required RSI/U-values for construction and efficiency/COP for HVAC were documented for each. For HVAC systems, the resultant characterization sets were then cross-referenced with the typical systems and efficiencies identified in the reference models (US DOE 2012), building code requirements (NRCan 1997, NRCan 2011a) and guidance documents (NRCan 2011b).

To validate the characterizations, the Delphi technique, a procedural research method involving repeated rounds of input by experts until consensus was reached (Linstone 1985, Barrett and Heale 2020) was used. This approach was widely used to develop best practice guidance in the absence of available data (Barkhordari Ahmadi, et al. 2023) and is increasingly adopted in the energy modeling context (Phichetkunbodee, et al., 2023). Two leading building science firms, each with substantial (200+) energy model databases of past project in both pre- and post-retrofit conditions supported this process, referring to their libraries of energy models to confirm or clarify the proposed characterizations. The code minimum construction thermal performance and construction assumptions were documented in a set of tables circulated to both consultant teams at this stage. Because of the limited service lives of HVAC equipment, likely replacement periods for each building set and the replacement equipment – whether like-for-like or an anticipated new type (e.g. oil boilers replaced with natural gas boilers) were also included in the HVAC system review table.

Two rounds of review were used, along with an in-person meeting after consensus was reached to present the final archetype inputs and provide a venue to identify any further issues warranting consideration or inclusion in the model. Finally, cluster analysis was undertaken to identify constructions and HVAC/energy systems with similar characteristics. For construction assemblies, clustering used effective conductivity ($\mathrm{Cond}_{\mathrm{eff}}$; Eq. 1) vs effective solar heat gain coefficient ($SHGC'_{\mathrm{eff}}$; Eq. 2) and both Euclidean and Mahanobilis distances were used with 2 to 15 tested.

$$\mathrm{Cond}_{\mathrm{eff}} = \mathrm{U}_{\mathrm{wall}} * (1 - WWR) + \mathrm{U}_{\mathrm{window}} * WWR \quad (1)$$

$$SHGC_{\mathrm{eff}} = SHGC_{\mathrm{window}} * WWR \quad (2)$$

The resultant construction and HVAC system inputs by period were then translated into EnergyPlus input files.

Retrofit development and prioritization

Retrofit scenarios were generated for each building archetype through a three-stage process for each of construction and HVAC system retrofits. In the first stage, the research team reviewed each of the base building combinations and identified the full spectrum of possible retrofits based on hygrothermal, thermodynamic, or practical considerations. For example, for building construction upgrades, insulation strategies that risked moving the freeze point into a porous cladding such as brick were avoided. Similarly, local/terminal equipment requiring high temperatures limited fuel switching to those capable of providing the appropriate temperature range. For practical reasons, retrofits requiring a complete replacement of all HVAC devices in a building or requiring the installation of significantly larger equipment were not considered as they were cost prohibitive.

In the second stage, the building consultants were again engaged through a Delphi technique where the researchers identified potential upgrades feasible for each a) construction and b) HVAC system type and created tables for each base condition to summarize these options. Notes regarding excluded retrofit options were also shared. These tables were circulated to the consultants for their review against their project databases and comments were received regarding any unconsidered technical challenges preventing listed retrofit measures, the frequency of such retrofits, and performance characteristics (i.e. revised U-value or COP). After another two rounds of review, consensus was reached, informing a range of retrofits representing different levels of ambition (Level 1 Most Typical (Short Payback) vs Level 2 Deep Retrofit) and for HVAC, retrofits enabled by the presence of a thermal energy network or ground-source heat pump system (Level 3). Again, an in-person meeting with all parties was held after retrofit finalization to present the results and provide an additional opportunity for clarification or refinement. The finalized retrofit inputs for both construction and HVAC systems were then characterized and translated into EnergyPlus input files. The final workflow is shown in Figure 3.

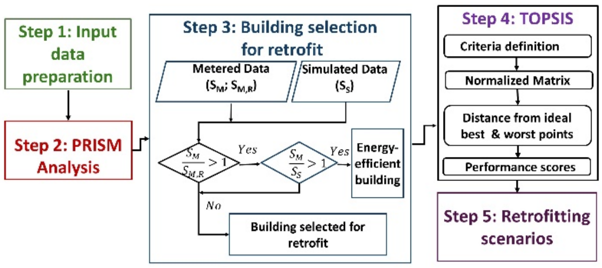

Figure 3. Building portfolio retrofit prioritization workflow

To further support transparent and data-driven retrofit prioritization, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was employed as a multi-criterion ranking method. Buildings were evaluated using a combination of measured and simulated indicators, including heating sensitivity slope, energy use intensity, total annual energy consumption, and volume-to-area ratio. After normalization, each building's distance to ideal and negative-ideal solutions was computed to derive a composite performance score. By integrating operational performance metrics with physical characteristics, this approach enables a balanced and justifiable ranking of retrofit candidates, ensuring that investment decisions reflect multiple dimensions of energy impact and align with broader energy and policy objectives.

Integration

Once the structural components of the model were defined, their composition was formalized through workflows, whose primary function was to manage the flow of data from external sources to one or more models, execute those models, and collect and distribute the resulting outputs. Regardless of the specific model being managed, each workflow follows a common sequence of fundamental steps: importing heterogeneous input data from proprietary formats, filling data gaps using archetypal data for construction, usage and energy systems and converting them into a shared central data model; optionally pre-processing these data through cleaning, calibration, pruning, or compression; optionally constructing or adapting model structures based on input characteristics such as building geometry; running the selected models one or multiple times using appropriate data exporters and model-specific input formats; retrieving and standardizing model outputs back into the central data model; and finally delivering the results through files, visual interfaces, or availability for subsequent workflows and external applications. This standardized workflow structure ensures interoperability, extensibility, and consistent data handling across diverse models, use cases, and urban-scale analyses. The re-running of the cases was crucial to obtain retrofit results once the model was validated.

District energy network optimization

To evaluate the impact of building retrofits on a district system, a 5th generation (heat recovery) thermal energy network (TEN) assessment/feasibility tool was developed in MATLAB to identify thermally balanced micro-TENs within urban blocks. The tool reads hourly building heating/cooling time series from building-specific EnergyPlus simulations results in Excel format and assembles a matrix in which each column represents one building's 8,760-hour profiles. After the building with the highest net heat rejection was selected as an anchor, the remaining buildings within the block were considered in n={1,2,3} sets to support adding building pairs with complementary net heating and cooling loads. Building profiles were aggregated along with the thermal storage state (charge/ discharge) to compute the outstanding mismatch, which then informs inclusion/exclusion decisions for the remaining candidate buildings. An objective function (Eq. 3) was used with forward selection to minimize the total energy imbalance, $Q_{net.}$

$$minimize\ Q_{net}(t) = \Delta Q(t) + Q_s(t) \quad (3)$$

where: ΔQ was the instantaneous imbalance of connected buildings, and Q_s was the energy stored or used from storage. stored energy available. This method was applicable for both baseline and retrofit cases, along with future development scenarios.

Building energy simulations were performed using the EnergyPlus engine, with all archetypes translated into IDF input files and simulated at hourly resolution. Model calibration and validation were conducted using measured utility data where available. In the Montreal case, statistical calibration was performed using the PRISM method, enabling the derivation of heating sensitivity and base load parameters, which were compared against simulated outputs. At the portfolio level, kernel density estimation (KDE) was used to define representative performance benchmarks. The resulting simulated energy use intensity (EUI) values were found to be consistent with measured datasets, with deviations generally within typical UBEM uncertainty ranges reported in the literature (<10–20%). In data-scarce contexts such as Toronto, archetypes were validated through expert-based Delphi processes informed by large databases of calibrated energy models (>400 cases).

Results

Construction characterization

Figure 4 shows the evolution of building codes (left) along with representative architectural styles (right) across periods. The overlapping of styles across multiple instances of the building code, along with differing residential vs non-residential code requirements led to an initial 23 archetypes, validated using Delphi technique.

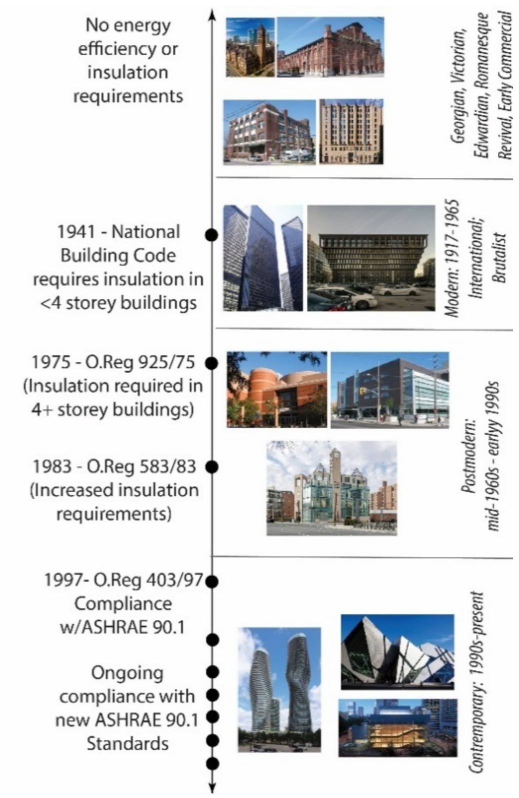

Figure 4: Timeline showing Architectural Styles Subdivided by Evolving Building Code Thermal Performance Requirements

Cluster analysis (Figure 6) was then used to identify buildings with highly similar thermal performance – both with respect to conductivity (area-weighted U-value/RSI) and radiation (area-weighted solar heat gain coefficient (set to 0 for opaque walls) – reducing the set to nine distinct construction characteristics.

The clustering exercise identified eight clusters and while the resultant areas and cluster identification orders were different, the cluster assignments themselves were identical for both approaches. The resultant construction assembly clusters are: {1975-2004 low-rise (brick), mid-high rise (concrete), and high-rise (steel) structures; 1975 -2004 Mid/High rise office (spandrel panel Postmodernist); 1975-2004 MURBS (all); 1941 1975 Mid/High rise office (curtain wall international); 1941-1975 mid/high rise offices (brick); All pre-1940 buildings + 1941-1975 low-rise MURBs; 1941-1975 low-rise office (brick) and mid-high rise MURBs (brick); 1941-1975 mid/high rise office & MURBs (concrete)}. These were uploaded into the CityRetrofit tool and mapped by address to each of the buildings based on year of construction and type. The input data for all clusters is published online at: https://github.com/DanaAlJadaa/Pre-2004-Canadian-CZ5-Envelope-focused-IDF-models.

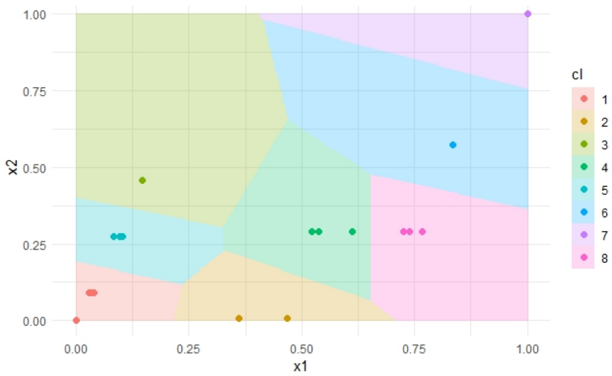

Figure 5: Construction Clustering using Euclidean Distances

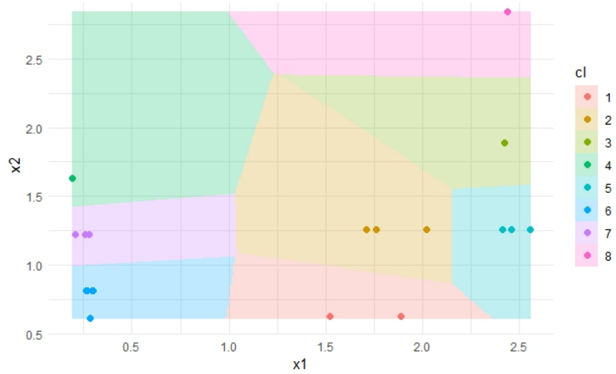

Figure 6: Construction Clustering using Mahanobilis Distances

HVAC system characterization

The HVAC system characterization identified nine representative HVAC systems across commercial offices and MURBs of various sizes, increasing the number of systems from DOE by two and providing more insight on shifts in fuel type (oil vs natural gas) and distribution (constant vs variable air volume) than the latter. These, with both baseline and the three levels of retrofit, were provided at https://github.com/jakjak42069/Baseline-E-Models-Canada-CZ5A. All other typologies were found to be consistent with DOE reference models, thus requiring no modification. Again, these were uploaded into the CityRetrofit library and mapped to buildings by type and period of construction.

District energy network optimization

The “Golden Mile” was an area within Toronto with significant planned densification (28,000 new residential units to be added (Fig 7, blue buildings) was used as a demonstration case, consisting of 35 buildings including a large grocery store used as the anchor. Results were shown after each iteration in Fig. 8.

Figure 7: Demonstration Area

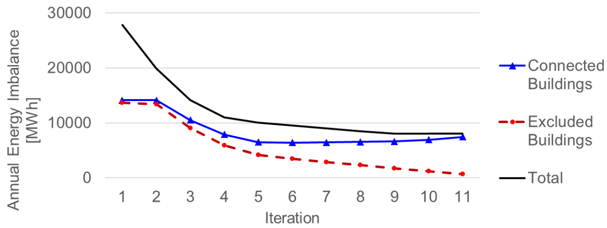

Figure 8: District interaction results

With this existing building set, 26 out of the total 35 buildings were identified for connection to the optimal TEN. This allowed 77% of the total heating and cooling loads to be met using heat recovery and seasonal storage, reducing the total heating and cooling energy required from by 77%, from 32,065 MWh/year to 7,449 MWh/year. The remaining load must be met from other sources, whether central (for the TEN) or at the building-level. Compared with individual building heat recovery using ground-source heat pumps with seasonal storage, the optimal TEN reduces net energy demand by 70%.

Platform integration and performance

In addition to the Golden Mile used for district interaction, the complete Toronto 2030 district (a 16km^2 area with over 30 million m^2 of built space across 7000+ buildings) has been integrated CityRetrofit tool (Fig. 10). The tool simulate up to 1,000 buildings in less than 1 hour using a single Intel® Xeon® E-2400 processor, with up to 8 cores at 95W, allowing the full district to be modeled in just over 7 hours, at which point the values were saved for future recall.

To use the tool, the building set of interest is identified, either through the GUI or by uploading a new set of buildings with archetype mappings as a .csv. Sample visualizations selected for implementation of the tool ae shown in Figure 10 alongside baseline energy consumption data.

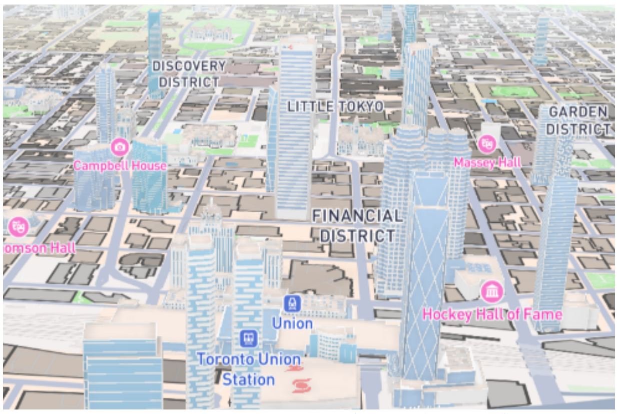

Figure 9: Toronto 2030 district (cropped)

Discussion and conclusions

The CityRetrofit platform presents a cost-effective way to create UBEMs suitable for retrofit pathway analysis at the portfolio, district, or city scale. Extending the tool to a new jurisdiction requires any new envelope constructions and HVAC/energy systems not already in the library to be added, which can be done by appending csv files.

Compared to existing UBEM platforms such as CitySim, UMI, or UrbanOPT, which are typically built around specific simulation engines or predefined workflows, CityRetrofit adopts a modular, data-centric architecture that decouples data models from simulation engines. This enables interoperability across tools, automated data ingestion from heterogeneous sources, and scalable application across jurisdictions with varying data availability. Additionally, the integration of empirical calibration methods (PRISM) and expert-informed

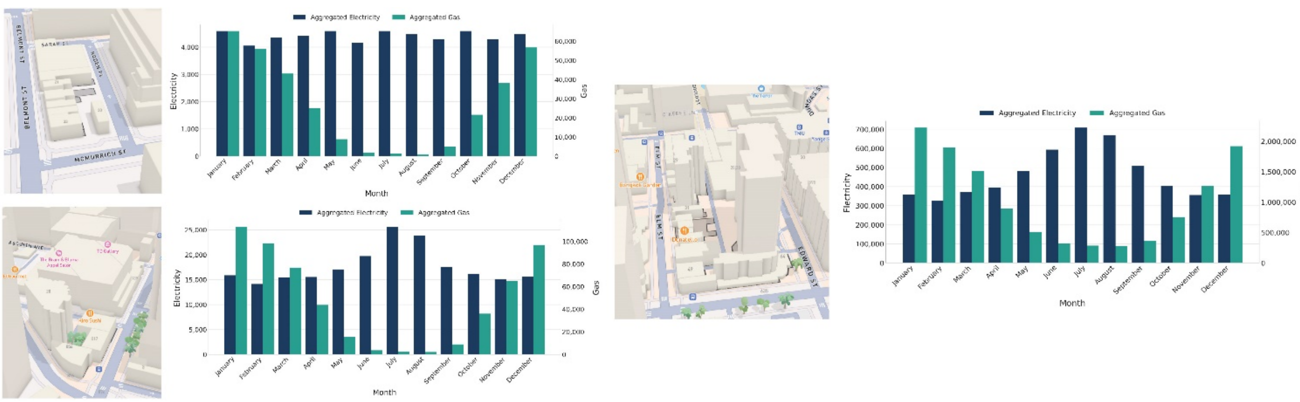

Figure 10: CityRetrofit sample visualizations (baseline condition)

archetype refinement provides improved adaptability in both data-rich and data-scarce contexts.

There were some limitations of this work. First, the lack of publicly available building energy data has made it impossible to validate the archetypes using utility so the Delphi study, informed by over 400 calibrated energy models, was used to confirm archetype inputs. Negotiations are ongoing to obtain access utility data for archetype calibration purposes and thus confirm the accuracy of these inputs. Second, the current modeling is single-zone only; multi-zone (by storey) is currently being tested for integration into the tool. Third, only forward-selection has been integrated for TEN optimization; future research will incorporate Backward Elimination and a binary Genetic Algorithm using tournament selection and uniform crossover, enforcing anchor buildings to remain included in all chromosomes. Finally, while the archetypes developed have been fully integrated into the back end of the platform and the district energy models are running, the full Toronto 3D model has not been loaded into a web-hosted platform and thus the Montreal GUI has not yet been implemented for the Toronto case. This is anticipated to be completed by August 2026.

Data Availability Statement

The full set of archetypal construction and HVAC system baseline and construction retrofit inputs were available in EnergyPlus format on GitHub as noted in the manuscript. The repository for the tool presented is available at https://ngci.encs.concordia.ca/gitea/CERC/hub.

Acknowledgments

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