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Developing a prototype building energy model for a Quebec primary school and assessing the importance of detailed HVAC system modeling

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Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*
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présenté par **Kato VANROY**
en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*
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RÉSUMÉ

Bien que le Québec bénéficie d'une électricité décarbonée et bon marché, le secteur des bâtiments représente toujours une source d'émission de gaz à effet de serre (GES) notable dans la province. L'électrification du chauffage des bâtiments institutionnels est donc au coeur des préoccupations des politiques de réduction des émissions de GES de la province.

Les modèles énergétiques de bâtiment permettent de quantifier l'impact de différentes mesures d'efficacité énergétique et de décarbonation, mais leur application à un parc de bâtiments nécessite une approche différente de la modélisation individuelle des bâtiments. L'utilisation d'archétypes, ou de modèles prototypaux, est souvent privilégiée dans ce contexte. Cependant, les efforts pour développer de tels modèles sont importants, et il n'existe pas à ce jour de base de données de modèles spécifiquement développée pour le contexte québécois. De plus, les configurations de systèmes de chauffage, ventilation et conditionnement d'air (CVCA) et leurs paramètres de design et d'opération ont un large impact sur les aspects de consommation d'énergie, d'émissions de GES, et la demande de pointe d'électricité. Or, ces systèmes sont souvent négligés, simplifiés ou uniformisés lors de l'établissement des modèles de référence, en raison du manque d'information et de la complexité de leur modélisation.

Ce travail de maîtrise vise à établir un modèle prototypal d'école dans le contexte québécois et à évaluer l'impact de différents systèmes CVCA sur la performance énergétique des modèles obtenus. L'école primaire a été choisie parce qu'elle représente un grand pourcentage des bâtiments institutionnels québécois et de leurs émissions de GES.

Le parc des écoles québécoises est d'abord caractérisé à partir de différentes études et bases de données, en accordant une attention particulière aux systèmes CVCA . Le modèle prototypal développé correspond à une école de 1640 m^2 incluant une salle de gymnastique. Les caractéristiques thermiques et géométriques sont fixées pour représenter des valeurs typiques du parc, tandis que plusieurs variantes de systèmes CVCA sont comparées. Le modèle de base utilise des plinthes électriques pour le chauffage et est ventilé naturellement, ce qui représente un système minimaliste pour une configuration de base. Des configurations avec systèmes à eau centralisés (chaudière et/ou refroidisseur) et des systèmes de ventilation de complexité variable sont ensuite définies. Au total, 9 variantes sont ainsi évaluées en détail. Les résultats montrent que les différents types de systèmes, mais aussi leur dimensionnement et leur stratégie de contrôle, ont un impact notable sur les consommations énergétiques mensuelles, annuelles, et sur la demande de pointe. Cette étude démontre que les résultats obtenus à partir du modèle prototypal pour évaluer des mesures de décarbonation (par ex. électrification

du chauffage) et d'efficacité énergétique (par ex. utilisation de pompes à chaleur) seraient largement influencés par les hypothèses de sélection et de configuration des systèmes CVCA. Les options de modélisation, c'est-à-dire la simplification plus ou moins grande des modèles sélectionnés pour représenter un processus, ont également un impact sur les résultats.

Le travail présenté dans ce mémoire a mis en lumière l'importance de prendre en compte la spécificité du contexte québécois et de considérer les différents systèmes CVCA dans le développement de modèles prototypaux ou "typiques". Au-delà du choix des systèmes lui-même, leur dimensionnement et leur contrôle doivent également être considérés en évitant de recourir aux options par défaut des logiciels telles que l'auto-dimensionnement. Nous proposons donc un modèle prototypal avec une géométrie et des paramètres thermiques uniques, et plusieurs variantes de systèmes CVCA. Il serait intéressant de raffiner les autres aspects du modèles, qui ont été simplifiés ici pour se concentrer sur les aspects liés aux systèmes CVCA.

ABSTRACT

With the rising pressure to reduce greenhouse gas (GHG) emissions, and ambitious targets being put in place, governing bodies are introducing policies and regulations to help achieve those goals. While the electricity-mix in Quebec has a low carbon intensity, energy consumption in buildings still results in high carbon emissions because of the persistent use of fossil fuels for heating. To assess decarbonization strategies on the building stock, building energy models (BEMs) are used to simulate different scenarios and decisions on implementing policies. To represent a building stock without simulating every building individually, these models rely on archetypes or prototype models, which must be defined and parameterized to represent all relevant characteristics of the buildings. Developing these prototype models represents a significant effort requiring detailed data on the building stock. Libraries of models are available to represent the US building stock, and these models are sometimes applied (as-is or adapted) to the Canadian context. There is still a lack of prototypical models developed specifically for the Quebec context.

Heating, ventilation, and air-conditioning (HVAC) systems configurations, as well as their design and operation parameters, have a significant impact on the energy use, GHG emissions, and peak power demand of simulated buildings. However, these systems are often simplified and/or unified for prototype buildings, because they are complex to characterize and to model.

This thesis aims to develop a prototype model for a school in the Quebec context, and to assess the impact of different HVAC systems on the energy performance of the model. A primary school was selected, as this type of building accounts for a large percentage of institutional buildings in Quebec and their GHG emissions.

In a first instance, the school building stock in Quebec is characterized, paying a special attention to HVAC systems. The prototype model represents a 1640 m^2 primary school, equipped with a gym. Thermal and geometrical parameters, gains, and schedules are fixed to represent typical values, while several HVAC system variants are modeled. The base model uses electric baseboard heating, and relies on natural ventilation, representing a minimal system. Centralized HVAC systems with water loops are then modeled, served by a boiler. Additionally HVAC systems with active cooling are modeled. Ventilation systems of increasing complexity are modeled. In total, 9 system variants are implemented in the model.

The detailed results show that design and control parameters have a significant impact on

dynamic profiles and monthly (or yearly) energy use, highlighting the necessity to carefully consider these aspects when developing prototype models, instead of relying on default configurations. The results provide evidence that the conclusions obtained from the proposed prototype model regarding decarbonization scenarios, such as switching from gas boilers to electric boilers, would be largely influenced by the variants used (or ignored) in assessing these scenarios. Similarly, assessing high-efficiency solutions such as heat pumps and investigating the impact on energy use and peak demand would require selecting the appropriate configuration—or configurations—to obtain representative results.

This thesis also shows that, in order to model decarbonization scenarios accurately, attention must be paid to *what* to model (system configurations and strategies), *how* to model it (choosing models, configuring them, selecting control strategies). System sizing is mostly absent from discussions on prototype and archetype models development, and while no general solution has been found, this thesis is providing evidence that the auto-sizing procedures in building performance simulation software are not always adapted to Quebec schools—and probably not to other commercial and institutional buildings in the Quebec context.

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CHAPTER 1 INTRODUCTION

On a global scale, buildings represent about a quarter of greenhouse gas emissions tied to energy consumption [4]. In the province of Quebec, characterized by a low carbon-intensive electricity mix, the greenhouse gas (GHG) intensity of the building sector remains high, due to the challenges posed by a cold climate. For large consumers it is often economically more interesting to opt for fossil fuels as the energy source for heating, resulting in relatively low electrification in the commercial and institutional sector [1]. Educational buildings constitute an important portion of the building stock, and the share of fossil fuels in their energy mix is amongst the highest of all sectors [1].

A large part of the school building stock in Quebec has been constructed over 60 years ago and has come to the end of its first life cycle, meaning important renovations are due [5]. Large budgets are reserved for this purpose [6]. Considering their contribution to carbon emissions, these investments have to be future-proof if we want to move towards a lower carbon-intensive building stock and achieve the ambitious carbon emission targets put in place by governing bodies.

Building energy models (BEMs) are an important tool used to evaluate decarbonization strategies and help decision-makers implement the most efficient measures to reduce carbon emissions in the building sector. There is a special interest in making models available for studies on the educational building stock in particular.

For the application of BEMs on building stock level, a differentiation is often made between prototype and archetype models. A prototypical model is a detailed description of a building, developed to represent the average characteristics of a whole building sector [7]. They are used in energy performance bench-marking, energy usage forecasts and predictions, energy use contributions of building components, and support of energy policies and standards. An archetype is used for urban scale modeling and is characterized depending on the specific purpose of the study in which it is applied [8].

The field of building energy modeling is quickly advancing and application opportunities keep extending. Prototype BEMs have been in use for decades but are continuously being improved with the evolution of building energy simulation software and the increased availability of large-scale data. In recent years, urban building energy modeling has been on the rise as a tool for urban planning and neighborhood-level energy system design. Different approaches to urban scale modeling exist and continue to be developed, but often archetypes are used to represent a larger group of buildings with similar characteristics. The use of archetypes reduces the number of simulations that need to be run and simplifies the modeling process to use only typical characteristics of a building group, rather than collecting detailed data on individual buildings, which would be impractical.

The workflow to create archetype models is still a subject of research. The main challenge when creating models for simulation on a large scale is determining the right model inputs. There is a lack of detailed information on buildings on larger scales, which is why archetype creation often relies on prototype model inputs, for which extensive time is spent on collecting and analysing data on buildings to identify the most pertinent characteristics.

Archetype models aim to simplify elements that have little impact on simulation results, while accurately representing those elements that play a more important role. Much research has gone into determining the sensitive inputs for BEMs, but these studies generally only look at the thermal properties and internal gains of a building.

In most studies using archetypical models, HVAC systems are largely simplified, or an estimation of consumption is obtained by simply multiplying the buildings thermal loads by average efficiencies [9]. This is acceptable for certain studies, but with the goal in mind to use these models to simulate decarbonization strategies, the inclusion of detailed HVAC systems can play an important role. This is further supported by the increased emphasis of providing homogeneous simulation inputs within standardization such as the ASHRAE Standard 205 project [10], aiming to create a standardized format of sharing HVAC performance data for use in energy simulation software to facilitate characterization of HVAC systems in BEMs.

Some public databases of prototypical models for commercial and institutional buildings exist [11] [12]. They are developed for use in building stock-level studies, but are also often adapted for application in UBEMs [13]. These models have been developed for the U.S. building stock however, and are thus not necessarily representative of buildings in Quebec.

With the push for renovations because of degraded infrastructure in school buildings, there is a need for prototypical models adapted to the Quebec context as a tool to help implement energy-efficient retrofits. Available data on school consumption has shown that the type of HVAC system installed has an impact on energy use intensity (EUI). Keeping in mind the extended application of prototype modeling inputs in urban energy models, this raises the question: can we have a better correspondence with real energy consumption patterns when providing a more detailed implementation of the HVAC systems in our archetypes?

Primary schools constitute the largest number of educational buildings in Quebec [5] and are thus the focus of this research.

1.1 Research objectives

This thesis presents the development of a primary school building prototype model using the whole building energy simulation program EnergyPlus, with special attention paid to the modeling of HVAC systems. Besides the development of the prototypical model itself, the research aims to investigate the importance of including detailed HVAC systems models in BEMs used to assess the impact of decarbonization measures.

The research consists of the following steps:

1. The school building stock is analysed and typical characteristics are identified.
2. A prototype model with the most common features is created to represent a "typical" primary school building.
3. Variations of the base model are made, implementing different possible HVAC configurations.
4. The energy use profile of both the base model and the variations are analysed and the impact of the representation of HVAC systems is discussed.

1.2 Thesis outline

Following this introduction, Chapter 2 will give an overview of research on building energy modeling as well as studies performed on school buildings in Quebec. The characteristics of the school building stock are presented in Chapter 3. Chapter 4 details the development of the prototype model and the variations. The simulation results will be analysed and compared in Chapter 5. The conclusions and final discussion can be found in Chapter 6.

CHAPTER 2 LITERATURE REVIEW

2.1 Building energy modeling

Building Energy Models (BEMs) are used to simulate the thermal loads and energy performance of buildings. On the individual building level, they are used to support architectural and HVAC system design, and to assess building performance and code compliance. On a larger scale, they are used to support the development of building energy codes and the implementation of policies. Another large-scale application that has been gaining interest in the past few years is urban building energy modeling (UBEM), where the energy use of buildings is simulated on a neighborhood- or city-scale for the evaluation of decarbonization scenarios [8].

2.1.1 Modeling approaches

For BEM application on large scale there are two main approaches: top-down and bottom-up methods.

Top-down

Top-down models use aggregated data on a large scale to evaluate the energy consumption in relation to different drivers, which can be socio-economic, technical, or physical [14]. Top-down methods are great tools for statistical analysis on building energy consumption, but the possibility to link building characteristics to energy use is limited, and they do not allow analysis at higher spatial resolution.

Bottom-up

Bottom-up approaches are based on models that represent buildings at an individual level. Disaggregated simulation results are combined to come to conclusions on different levels of the building stock. A large quantity of data is needed for bottom-up models to capture the energy behavior of the building stock well, which is currently the largest limiting factor in their development.

Bottom-up models can be further divided into statistical, physics-based, and hybrid methods. Statistical methods use billing information to project energy consumption based on influencing variables such as building descriptors and socio-economic factors. They are robust but they do not allow predicting energy use on a more granular time scale and can not incorporate the combined impact of different measures at the same time [8]. Physics-based models use thermodynamical principles, taking into account heat and mass flows to estimate a building's energy consumption based on its characteristics. Hybrid models combine features of physics and statistical-based methods.

The complexity of physics-based models ranges from simple steady-state models using a single zone to whole-building dynamic simulation engines.

Models such as resistor-capacitor network models are common, but are limited in their use [15]; only simple energy conservation measures can be studied. For more complete studies that concern cross effects between building systems, a more detailed, physics-based simulation engine should be used. Several simulation tools exist that allow dynamic simulation of whole buildings such as DOE-2, TRNSYS, IES VE and IDA ICE, but EnergyPlus [16] is most commonly used by researchers [17].

For application on large scale, since it is not feasible to model each building individually with detail, a common approach is the use of prototype or archetype models, where a single model represents a larger group of buildings. The results are extrapolated to the building stock by multiplying the simulation results with the number of buildings or the floor area of the stock represented by the archetype. Archetypes are the results of two processes known as segmentation and characterization [18]: the first one categorizes buildings according to their physical parameters, and the second one aims at assigning ranges of values to the parameters of models (or archetypes) in each segment of the building stock. Parametrized archetypes are then combined with frequency distributions to represent the building stock. A recent effort by the National Renewable Energy Laboratory in the US aims at integrating the results of two large-scale building stock models, known as ResStock and ComStock, to develop a typology of the US building stock usable to assess decarbonization measures at the national level [13].

2.1.2 Prototype VS. archetype

The concepts *prototype building model* and *archetype building model* are not always well defined within publications and are often used interchangeably. Both terms are applied in a context where they represent a "typical" building of a certain type. In many studies, however, there is an important nuance to how the respective models are developed and applied. To remove any ambiguity, the concepts are explicitly defined for their discussion in this thesis.

The term prototype building energy model seems to have been introduced in the 1980s in the context of representing "average energy consumption patterns and intensities of a specific building sector" [7]. Huang et al [19] did an extensive review of the work done up until that point on prototype modeling, summarizing the goals and approaches of creating prototype building models. They also created 481 prototypical models to obtain estimates of the consumption of the existing U.S. commercial building stock and assess the potential of co-generation [7]. These were later refined and used to estimate heating and cooling loads of U.S. buildings and study HVAC system efficiency. For the purpose of these types of studies, a complete building description is required, including detailed input on HVAC systems and operations.

Later, the U.S.-DOE developed a database of commercial and residential reference buildings and prototypes buildings [11] [20], to serve as a starting point for energy efficiency research [21]. Their goal was to model 70% of the U.S. commercial building floor area, with the intended use in “research to assess new technologies; optimize design; analyse controls; develop energy codes and standards, and to conduct lighting, daylighting, ventilation and indoor air quality studies" [21]. Specific emphasis is put on the fact that the models are not created for studies on a smaller scale than country-level, but that variations of the models can be made for such applications.

The term archetype is more commonly used in the field of urban building energy modeling. Urban building energy models (UBEMs) are a tool to predict or estimate building energy performance on the scale of a dozen buildings to a few thousand at a time. One approach to obtain consumption profiles of a large group of buildings is by clustering similar buildings together and representing them by building archetypes [8]. The way these archetypes are characterized depends on how the building stock is segmented and the specific questions to be answered by the study, allowing for certain simplifications depending on the context of the application.

As mentioned before, the terms are sometimes used interchangeably in literature. The term *archetype* is also used in the context of whole building stock applications [8], and the term *prototype* is in some studies used in the context of UBEM applications [22] [14] [23]. For the purpose of this study the two concepts are distinguished following the nuances discussed above.

A prototype model is thus defined as a building energy model which represents average characteristics of a building sector on a whole building stock scale. The model is a detailed description representing real building operation, mainly serving for use in code development and policy studies, but also serving as a starting point for development of variations for further applications. An archetype model is a model tailored to represent a group of buildings variable in size, characterized appropriately for the scale it is applied to and the study in which it is used.

2.2 Building energy modeling in a local context

If we want to conduct studies on a specific building stock using BEMs, it is necessary for those models to represent local buildings. This is not always easy since data to create those models is often not available or accessible.

2.2.1 Reference buildings for the United States

In the U.S. a major effort has been done by the Department of Energy to construct BEMs for energy analysis on commercial (and residential) buildings. Using data from the Commercial Buildings Energy Consumption Surveys (CBECS), a collection of prototypes is created representing the use-types of 70% of the commercial buildings' floor area.

The accessibility of these models and detailed documentation of their development makes them widely used by other researchers.

2.2.2 Reference buildings for Canadian locations

For Canada, and Quebec in particular, no such models exist at this point. This forces researchers studying the Canadian building stock to use models that are not adapted for this purpose, or create their own models with limited resources. Considering how time consuming it is to collect data to create new models, the models created by the DOE are often used for studies on Canadian buildings because of the proximity to the U.S. and parallels in building code.

In [24] and [25] the impacts of climate change on energy loads in buildings in Canada has been assessed using the DOE commercial prototype buildings. [23] looks at the impact of energy efficiency measures proposed in ASHRAE 90.1-2010, designed with the goal to achieve 30% energy savings in U.S. buildings, and looked at whether the same level of energy savings is achieved in a Canadian context using ASHRAE 90.1-2004 as a baseline. While these studies bring to light important impacts of climate on energy consumption patterns, they do not account for inherent differences in building stock.

A comparative study has been done between the characterization of BEMs according to ASHRAE 90.1-2010 and the Canadian National Energy Code for Buildings (NECB) 2011 to show relative energy savings for cities across Canada. The energy savings following NECB 2011 are up to 20% in some locations, showing the impact of adapting to local context on consumption patterns [26], while not taking into account any other differences in building characteristics such as differences in architecture or construction materials. In some applied studies, the DOE models are modified to better represent the Canadian building stock, as is done in [27] who adapted the models to adhere to the NECB. In other studies [28], archetypes are created using information on geometries of local buildings, but are complemented with templates based on DOE models for those inputs where local information is not available.

Natural Resources Canada (NRCan) is working on a framework for energy performance analysis of commercial buildings in Canada called the Building Technology Assessement Platform (BTAP). Part of the framework consists of the automatic creation of reference buildings for different vintages. The current effort focuses mainly on new construction, using recent building codes (NECB 2011, NECB 2015 and NECB 2017) to define model parameters. Work is being done on creating rule-sets for older vintages [29] [30]. The framework includes built-in commercial building types. These are based on the U.S.-DOE reference building models [11] and keep the geometries and space-types found therein. An extension is under development where a geometry can be created based on a basic description (floor area, number of floors, space-types), allowing an easier adaptation to local characteristics.

In the future, BTAP can hopefully be expanded to include rule-sets based on actual data on buildings to create a powerful tool that is readily available for researchers, covering a large base of functionality, allowing simulations of scenarios for new buildings as well as looking at retrofitting of the existing building stock.

2.2.3 Model development

To develop models for representation of a larger group of buildings, some assumptions and simplifications need to be made during the modeling process, both to reduce the modeling effort and to reduce the simulation time [21] [7] [31].

The DOE prototypical models include a single prototype BEM per use-type, class of construction year (pre-1980, post-1980 and new construction) and climate zone. No further distinction is made within these groups for example for geometry, construction type or HVAC-systems. Only the most common characteristics within a group are represented [21].

During the development of their prototypes for the U.S., Huang et al [7] have simulated the same building using two different ventilation systems, showing a 30% impact on yearly energy consumption. They concluded that separate equipment categories should be made, but found that for a lot of building types, the equipment does not vary much within a single building age group. In the development of the advanced design guide for K-12 schools in the U.S [32], the prototype models also include variations of HVAC systems to assure that conclusions on estimated energy savings are broadly applicable to the use-type. This shows that HVAC system differentiation is assumed to be important in modeling, but there is no specific discussion on the impact that different systems have on simulation results, and only general results on energy savings are given.

In recent years, more attention has been given to the HVAC system representation in building modeling. Most studies focus on assessing the accuracy of system representation amongst different simulation platforms (EnergyPlus, DOE-2, etc.) in order to compare modeling accuracy or bring to light shortcomings in the software's capabilities. A study modeling a datacenter in EnergyPlus and DOE-2 showed good correspondence between the two softwares [33]. A similar study compared simulation of different HVAC components in EnergyPlus, DeST, and DOE-2 using an ideal building model created to avoid differences across loads amongst the simulation platforms [34]. The differences in energy consumption were within 10%. A study comparing simulation of a university building in EnergyPlus and IES has reported that while the aggregated energy predictions correspond well, disaggregated results show important discrepancies between the two software tools. Especially on system level, small differences in system definitions and control can have large effects on energy predictions, concluding that model assumptions can have an important impact on simulation results [35].

Some studies are also conducted to validate the simulation's predictions for specific components using fine-tuned models [36], or to assess the impact on simulation accuracy of factors that are not yet incorporated in the simulation software such as HVAC faults [37].

Very few studies are done on the impacts of choices made with regard to HVAC systems within one modeling environment. Since EnergyPlus is one of the most widely used modeling environments [17], it raises the question of how much impact the choices in representation of the HVAC system have on the simulation results. EnergyPlus allows users to represent components with different levels of detail to allow a certain level of abstraction. A study has been performed on the impact of wind pressure coefficients in airflow modeling in EnergyPlus. Natural ventilation was modeled in a low-rise residential building on one hand with the default wind pressure coefficients calculated by EnergyPlus, which were compared to those calculated with a detailed CFD model, showing a very large impact on the air flow rate through the openings [38]. The software also supplies default values for many inputs if they are not specified by the user. Qinpeg has compared the modeling of air-handling units with VAV boxes in EnegyPlus to a high-fidelity model in Modelica [39], coming to the conclusion that applying default parameters in EnegyPlus can result in a NMBE of 41.5% for fan energy consumption.

This ability to model components at a higher level is used to simplify the creation of models, but we must ask ourselves if this step does not compromise the accuracy of the results.

2.2.4 Primary schools in Quebec

Primary school buildings in Quebec have been the subject of several studies. The Schola project [40] aims to put at disposition tools to aide in the renovation process by understanding the characteristics of the school building stock in Quebec envisioning what it can become, based on scientific research. Useful research papers and guides have been produced through the organization discussing different characteristics of schools.

A study on architectural characteristics has been done by Tremblay-Lemieux [2]. By analysing the building plans of 100 different schools, typologies were identified based on building form, distribution of classrooms with respect to the central hallway, location of a building on its premise, position of the gymnasium, features of annexes, and the position of the main entrance. These characteristics have been shown to be linked together and linked to building age as well.

A guide has been created summarizing this and other work done on Quebec schools [5] to help make sustainable decisions in renovation projects. The guide presents useful statistics on a wide range of building characteristics, including but not limited to information on building form construction and fenestration characteristics, space types and sizes and occupant comfort.

In view of energy transition in schools, a large study was done on the current use of thermal energy storage in school buildings [41]. Multiple buildings with thermal storage were selected for study and their operations were documented. In both [42] and [43], three buildings that recently transitioned from boilers using fossil fuels to electric thermal storage systems were studied. Detailed information on the schools' HVAC systems and operations before and after the installation of electric thermal storage was documented, and an analysing was done on the impact on energy consumption and peak demand.

A detailed description of school buildings in Quebec is done in the following chapter using amongst others the information presented in these studies.

2.3 Chapter overview

The literature review presented in this chapter has briefly reviewed the approaches used to apply building energy modeling at the scale of neighborhoods, cities, or larger building stocks. Bottom-up approaches based on physical models are preferred to assess energy efficiency or decarbonization measures. They are based on segmentation and characterization of the building portfolio, and simulation of a number of models representing "typical" configurations, known as archetypes or prototype models. Prototype models can also be used to assess changes to building codes, or other policy measures. Reference models have been available for a long time in the US, and these models have been used—in their original form or adapted—in studies addressing the Canadian context. But no database of reference or prototype building model specifically developed in the Canadian context is currently available. Studies have also found that HVAC systems can have a large impact on energy performance, as well as their representation in building performance simulation software. This aspect, however, is often given little consideration in developing reference models, compared to thermal properties or geometrical information. HVAC systems and their controls are the main aspects influencing the relative distribution of energy sources in the total energy use of a building (e.g. gas vs. electricity) and the peak demands. They should therefore be at the center of preoccupations when developing models to assess decarbonization scenarios.

This thesis intends to pave the way towards a library of prototype models adapted to decarbonization studies in the Quebec context by investigating school buildings in the Quebec context, proposing prototype model(s), and assessing the impact of different HVAC system selection and modeling approaches.

CHAPTER 3 CHARACTERIZING THE SCHOOL BUILDING STOCK

This chapter examines school buildings in Quebec in order to identify the modeling parameters for a "typical" school. Part of the information presented in the following subsections comes from the conclusions of the research presented in the literature review. These findings have been complemented by data obtained from public databases [44], survey data collected by Hydro-Quebec and used in developing SIMEB archetypes [45], and data on the energy use of educational buildings in the year 2016-2017 [3].

3.1 Generalities

In 2016, Quebec counted 3333 buildings used for educational purposes. Of those, 2308 are primary school buildings [5]. A more detailed breakdown of educational buildings per type is shown in figure 3.1. The data presented in this figure is based on property assessment data from 2019 and only takes into account the predominant activity type on a premise. The category "other" comprises buildings labeled as mixed education with both primary and secondary grades, kindergartens[1] and then a few unique types of education, such as for example homeschooling.

Because of the predominance of primary schools in the building stock, they have been the main focus in most previous studies and will be so for this study as well. The consumption data on schools [3] and the survey data [45] cover larger scopes of the educational building stock. For these two sources, the type of education taking place in the buildings is not included in the data. The characteristics of the buildings can thus not be linked back to the type of educational building. This has to be kept in mind when using the data.

Over 60% of primary school buildings in Quebec were built between 1945-1965. Because of the implementation of compulsory education and increased birth rates, the number of school-attending children increased and pushed the construction of a large number of schools [5]. The schools constructed during this period focused on simplicity and efficiency, favoring natural lighting and ventilation and allowing quick construction. This resulted in typical rectangular forms with a central hallway and rows of classes on each side, as shown in figure 3.2, and are the dominant geometry seen in the school building stock [2, 5].

In the following sections, the geometry of the buildings, the energy consumption, and HVAC

[1] The reason why kindergartens have such a low presence in this chart is because they are often integrated into primary schools and rarely are the main use of a building.

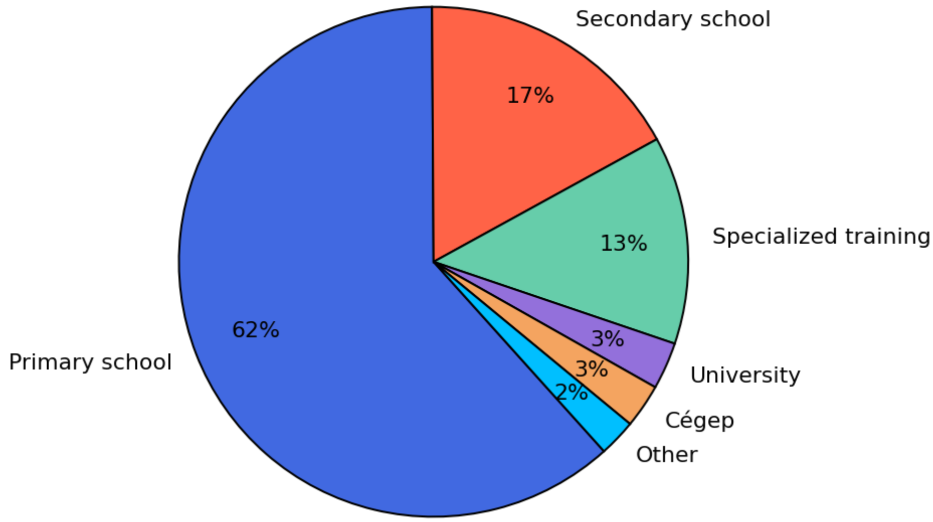


Figure 3.1 The number of schools per type for all of Quebec

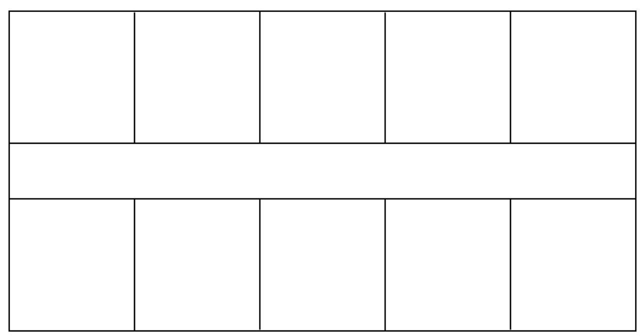


Figure 3.2 A typical structure of a primary school building with central hallway

systems will be discussed. But first the complementary data sources used for this characterization are elaborated.

3.2 Complementary data sources and treatment

Several data sets covering a larger scope of the educational buildings in Quebec are used. Through GeoIndex [44] and a repository by Microsoft on github [46], georeferenced data sets are made available on building geometries and building premises in Quebec. Then there is data listing all educational buildings with general information on the building as well as energy consumption for the year 2016-2017 [3].

The treated survey data [45] gives detailed information on school geometries, building properties and HVAC systems. This data combines information collected through three studies conducted by Hydro-Quebec between 1991 and 2007 on commercial and institutional buildings.

3.2.1 Geospatial data

Two geospatial data sets are mainly used in this study. The first data set, made available by Microsoft [46], contains the geometries of all building footprints in Quebec. Because we are interested in characterizing geometries of schools, building footprints can help determine tendencies in the general form of the building. The geometries provided by Microsoft are generated automatically from aerial images and thus contain no information on the footprints other than its location.

The footprints produced by Microsoft use an automatic approach, allowing the data to have a complete coverage of the province[2]. Other sources of footprints are available for some municipalities and can be more accurate, but the Microsoft footprints were deemed to be acceptable for our study after some specific comparisons were made for known schools in the Montreal area.

The second data set is the Property Assessment Data (*Unités d'évaluation foncière* or UEFs) of all premises in Quebec (in 2019) [44], giving information on the predominant use of terrains. The attributes linked to the terrains which are relevant to here are listed and described in table 3.1. The "Use type code" allows selecting only those terrains used for educational purposes. The data used is however not perfect, some land plots are wrongly identified and information linked to them can be wrong or missing.

Given the fact that the footprint geometries do not contain any additional information, it is not possible to identify which footprints are of school buildings, and which are not. The geographic component of the data makes it possible to link them to the UEF data. Any footprint geometry whose centroid falls within the boundaries of a school premise will be selected as a school building. We have now obtained a collection of all [3] building footprints of schools.

The UEF data is principally used to identify school buildings, but also gives access to additional data on building properties. Information on the number of building floors is available for 88% of of the footprints, but the quality of the data is unknown.

[2]Footprints for the other Canadian provinces and territories are also available.

[3]Within the limits of the completeness and accuracy of both data sets used to do so and the limits of the automatic treatment of this data

Table 3.1 The attributes linked to the UEF geometries and their descriptions

Attribute	Description
ID	A system unique identifier
Registration number	Registration number for the property assessment roll
Use type code	A 4-digit code identifying the dominant usage of the land, following the classification by *Codes d'utilisation des biens-fonds (CUBF)*
Construction year	The construction year of the building(s) on the property
Address	The street name and street number(s) of the building(s) on the premise
Number of floors	The number of floors above ground of the (tallest) building on the property (in case of multiple buildings)

3.2.2 Energy use data

A list has been provided with the energy consumption in the year 2016-2017 for all educational buildings (preschool, elementary and secondary levels) managed by the boards of education in Quebec [3]. The list contains supplementary information on each entry as elaborated in table 3.2.

The list entries are for *buildings* and not necessarily entire *schools*. Because individual pavilions can have their own entry in the data, but aren't necessarily disconnected from central systems in a school, this can result in entries with seemingly inconsistent data. In some cases they have a relatively low or high energy consumption with respect to their surface area, indicating that there are shared meters or energy systems with other buildings on the terrain for which the energy consumption is only attributed to one of them. In an attempt to remove this bias, the building addresses (street name and postal code) have been used to combine data of buildings at the same address. An example of how this improves the data quality is given in table 3.3. The example shows how some of the individual entries have abnormally low or high EUIs, while the combined entry has an average EUI.

For easy identification of some important factors impacting a buildings energy consumption, a classification system is put in place by *le Ministère de l'éducation et ministère de l'enseignement supérier (MEES)*. There are 28 possible codes, as shown in table 3.4.

The meaning behind the letters and numbers in the code are explained as follows (definitions

Table 3.2 The attributes linked to the consumption data on schools and their descriptions

Attribute	Description
Building ID	A unique ID for each building, also linking buildings to their administrative region
School Name	The name of the school (building)
Building address	The address of the building with civil number, street name and postal code
Type	A classification code indicating the principal source for heating and the complexity of ventilation & cooling systems
Surface area	The total floor area of the building(s)
Energy consumption	The annual energy consumption, classified per energy source

taken from MEES [47]):

- E : Electricity is the main source of heating.
- G : Natural gas is the main source of heating.
- M : Fuel oil is the main source of heating.
- S : The building is a 'special' case.
- V : The majority of the building is mechanically ventilated.
- C : The majority of the building is cooled by a mechanical system.
- 0 : There is no swimming pool, no heavy duty workshops and no food service.
- 1 : There is at least one heavy duty workshop or kitchen for food service. There is no swimming pool. (A heavy duty workshop is defined as a space with a ventilation rate of at least 2 000 L/s).
- 2 : There is at least a swimming pool, with or without a heavy duty workshop or food service.

Table 3.3 An example of the grouping of entries by address

Building ID	Classification Code	Energy Consumption [GJ]	Floor Area [m^2]	EUI [GJ/m^2]
ID 1	EC0	7081.2	6444	1.099
ID 2	GV0	6025.6	10680	0.564
ID 3	G1	1837.8	4847	0.379
ID 4	EV1	428.0	7131	0.060
ID 5	GV0	4941.4	3773	1.310
[ID 1, 2, 3, 4 & 5]	[EC0, GV0, G1, EV1, GV0]	20313.9	32875	0.618

Table 3.4 The classification codes used to identify a buildings "Type" (MEES)

E0	EV0	EC0
E1	EV1	EC1
E2	EV2	EC2
G0	GV0	GC0
G1	GV1	GC1
G2	GV2	GC2
M0	MV0	MC0
M1	MV1	MC1
M2	MV2	MC2
S		

3.2.3 Combined data

The geospatial and consumption data sets present a lot of useful information by themselves. By using the address information present in both data sets, the data can be linked. The combination of those datasets could allow to develop region-specific archetypes or to perform more detailed analyses. In this study, we have focused on developing a single prototype building model with different HVAC system variants, so this cross-referenced information was only used to assess the relationship between geographical location and energy use intensity. This relationship was found to be weak, as will be shown in chapter 5.

3.3 Geometry

Previous studies have already characterized certain aspects of building form, but the studies were not performed with building energy modeling in mind. While the information collected is very useful, it does not consider all relevant information on geometry. The data on school building footprints is used to include some additional aspects on building form and characterize building geometry for energy modeling purposes.

Total floor area

In Figure 3.3 the distribution of total floor areas of school buildings is shown, as presented by Tremblay-Lemieux [2]. The floor area lies on average between 1800 m^2 and 4000 m^2, with the most frequent cases between 1500-2000 m^2. From all primary schools, 70% have a floor area between 1000-3000 m^2.

Using the information from the footprints and UEF data, an estimate of a buildings total floor area can be made by multiplying the footprints surface area with the number of floors. The data obtained is presented in figure 3.4. This data shows a slightly different trend, indicating a large number of buildings with a smaller floor area. It is important to note that the data derived from the footprints treats each building separately, even if they are part of the same school. It is assumed that the data presented by Lemieux treats schools as a whole, which could explain the different trend seen in the graph. Inaccuracies in the data could be another contributing factor.

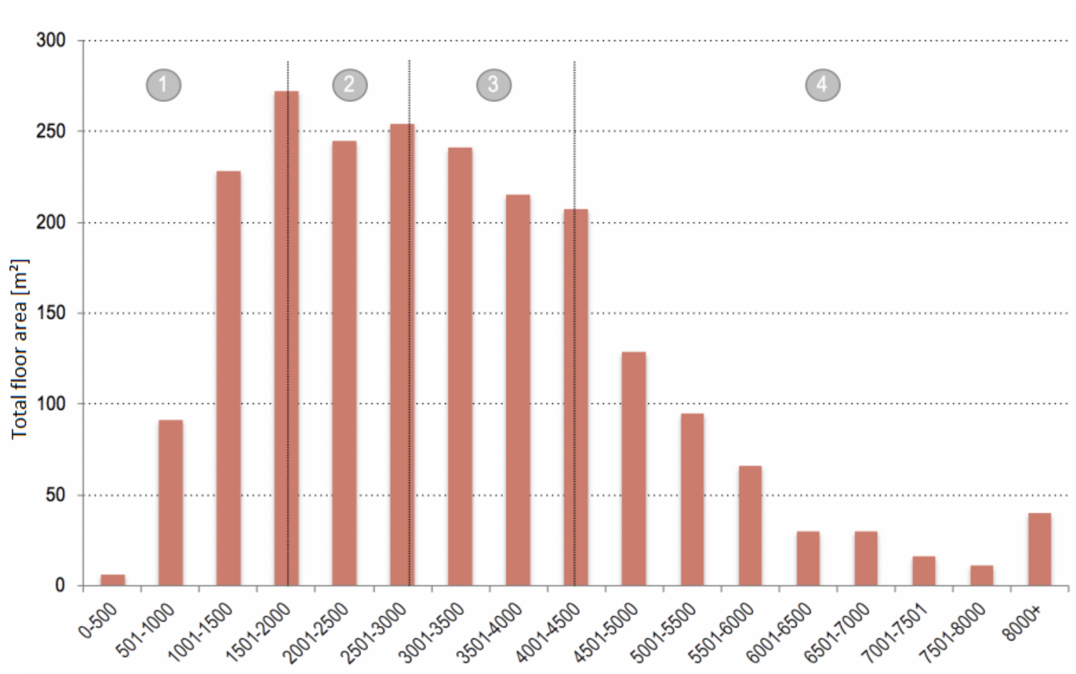


Figure 3.3 The number of schools according to their total floor area [m^2], from Tremblay-Lemieux [2]

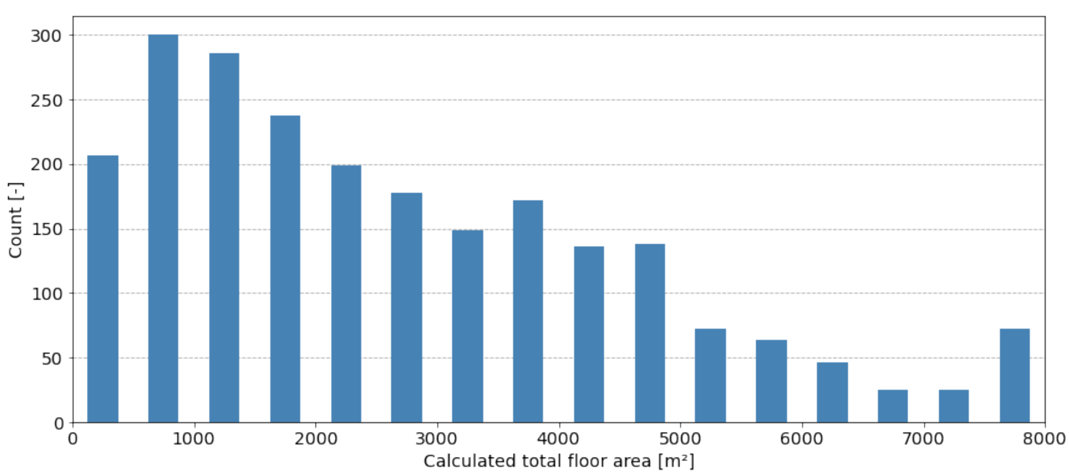


Figure 3.4 The number of schools according to their total floor area [m^2] derived from the footprint and UEF data.

Number of floors

The distribution of the number of floors coming from the UEF data is shown in figure 3.5 for both primary and secondary schools. The overwhelming majority of buildings has two floors. No detailed information on the number of floors from other sources was found, but the renovations guide [5] shows typical values for the different typologies of schools. Most typologies have two floors, only urban schools built in the 60's with a central corridor have typically 1 (or 2) floors, but this is not a common typology (5% of schools). The fact that single floor buildings are not typical, but do constitute around 25% of the schools according to the UEF data could suggest a lack of quality of the data, and would also explain the extend of the discrepancy seen in the total floor areas in figures 3.3 and 3.4.

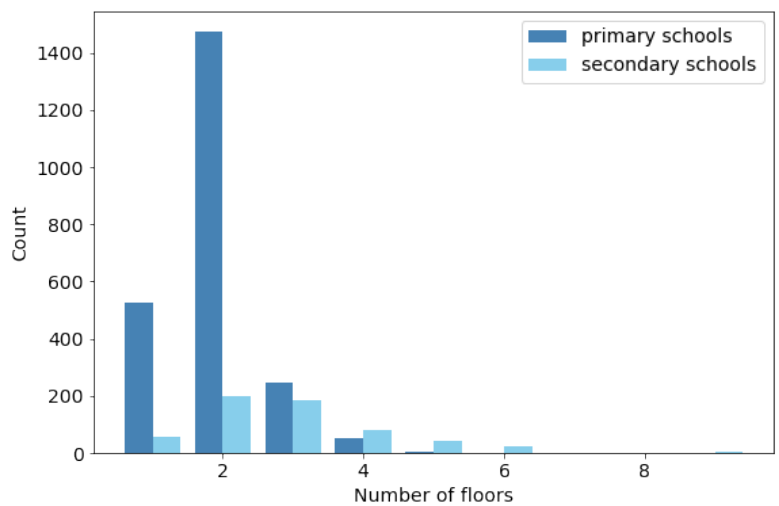


Figure 3.5 The number of schools according to their number of floors (UEF data)

Building shape

In her analysis, Tremblay-Lemieux looked primarily at form of building through the position of the hallway with respect to the classrooms. The dominant configuration, corresponding to 81% of the schools studied, was found to be a linear, central hallway. This implies a rectangular form of the building. Although the author noted the presence of several variations, and by extension includes buildings with an "L" and "H" shape to the category of linear circulation. This may be interesting in the view of architectural characterization, but for the purpose of envelope characterization for energy performance, these variations should be considered separately. A more rigorous categorization could be performed taking into consideration the relation between building envelope and volume.

In the literature, several indices are defined to characterize building envelopes for the purpose of energy modeling.

The relative compactness (RC) is defined as a function of building volume and envelope area as shown in equation 3.2. It is a factor shown to relate to building energy consumption in simulation [48]. Because of the uncertainty of the data on the number of floors, the height of the buildings has been taken out of the equation by only looking at the perimeter of the building footprint. This would be equivalent if all buildings were equal in height. While this is not entirely true (also due to variations in floor height), the compactness of the perimeter still shows useful information on the building form. A new index RC_{perim} is used, defined as the ratio of a reference perimeter to the perimeter of the footprint. The reference perimeter is chosen to be a circle with the same surface area as the footprint, as it the most compact shape a footprint could be.

$$RC = \frac{(V/A_{env})_{building}}{(V/A_{env})_{ref}} \tag{3.1}$$

$$RC_{perim} = \frac{P_{ref}}{P_{footprint}} \tag{3.2}$$

An analysis on building shape has been performed for primary schools alone but could be extended to entire educational building stock thanks to the extensive coverage of the data used.

There is a large spread in both footprint area and RC as can be seen in Figure 3.6a. For reference, the relative compactness of a square footprint and a footprint with aspect ratio (AR) = 1/3 are drawn. A building with an aspect ratio of 1/3 is already a relatively slim building. This means that a large part of the building stock has an ever higher envelope exposure, implying slim, complex shapes.

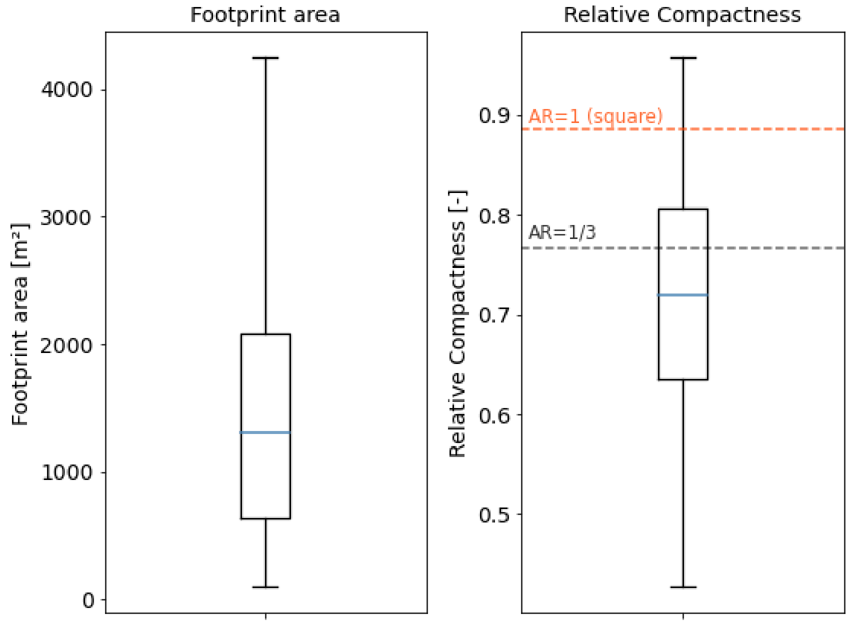
In an attempt to better characterize the variations in shape, building footprints were analysed based on their relation to a rectangular shape. Looking at both perimeter and area, footprints were analysed by their form and labeled as "rectangular" or "complex" shapes. By applying a function to the footprint geometries which approximates an arbitrary polygon by a rectangle, the change in perimeter and area was analysed to determine how close the original shape was to a rectangle. Using this classification, about 50% of the building footprints were determined to be rectangular, showing that while it is a predominant shape, it is not an overwhelming majority as described by Tremblay-Lemieux [2]. The same characteristics are plotted for rectangular buildings on their own in Figure 3.6b. While there remains a relatively large spread in footprint area, the range of compactness values is smaller, with about half the footprints having an aspect ratio between 1/2 and 1/3.

An important note should be made on width of a footprint. Figure 3.7 shows the spread of the width for the rectangular footprints. Half of the footprints have a width between 15 and 25 m, with an average around 20 m. This makes sense if we think back to the typical architecture of school building, prioritizing natural ventilation and lighting. This configuration limits the width of a building to the width of two classrooms and the hallway in between. Because classrooms have standard dimensions, the total width can be considered as a constraining parameter. Within rectangular buildings, a building will increase its aspect ratio with size, rather than increasing the building proportionally on both sides. Large buildings with a low aspect ratio are typically buildings with a central circulation loop and classrooms that have less access to natural lighting, as was the typical architecture for schools built in the 60's [5].

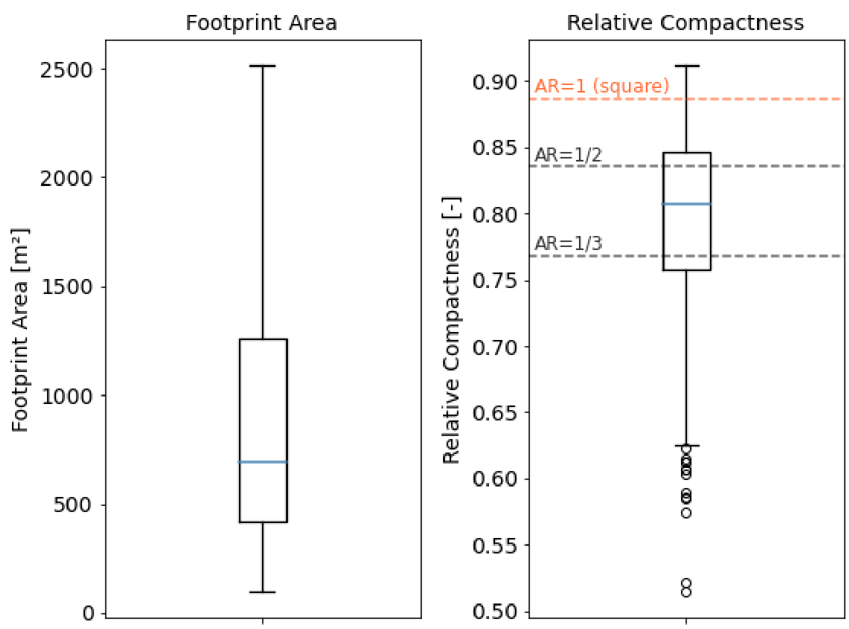
The complex footprints are not analysed further, because of the large variety in geometrical characteristics. Future work could look into the classification of complex geometries in an attempt to capture the most relevant information on their building shape and how it is translated into model parameters that best represent their impact on energy consumption for a typical model.

Roof type and building form selection

Two thirds of primary school buildings have a flat roof [5]. Based on this analysis, a rectangular shape with a footrpint area of 1000 m^2 and a width of 20 m has been identified as a representative building form. The building is assumed to have two floors and a flat roof.



(a) All footprints



(b) Rectangular footprints

Figure 3.6 The spread of area and relative compactness of footprints, for all footprints (n=2600) (a) and rectangular footprints only (n=1263) (b). The outliers for the footprint area have been removed for readability of the graph.

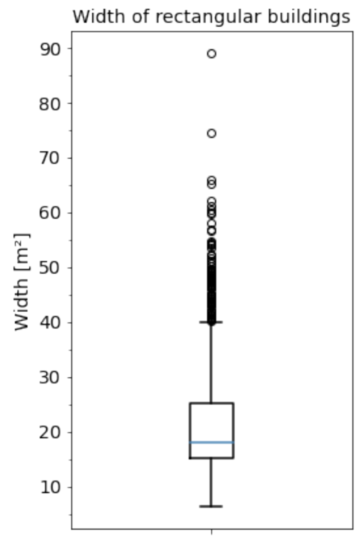


Figure 3.7 The spread of the width of rectangular building footprints

3.4 Energy consumption and HVAC systems

3.4.1 Trends in the Quebec building stock as a whole

One of the aspects to be considered in system modeling is the energy sources used by the equipment. In contrast to most regions with cold climates, in Quebec the heating equipment is largely electrified, especially in the residential sector. In commercial and institutional buildings, including schools, the use of fossil fuels remains dominant. Statistical data on energy consumption of the building stock by sector is available in the Comprehensive Energy Use Database (CEUD) [1]. Looking at the energy use on an aggregated level, as shown in table 3.5, fossil fuels[4] represent the smaller share of the total energy consumption. When looking at the real energy consumption of individual buildings, it becomes clear that there is not a homogeneous consumption pattern and the part of individual buildings' total energy consumption that consists of fossil fuels varies largely. Figure 3.8 shows the share of secondary energy use that comes from fossil fuels for about 200 buildings managed by the city of Montréal, which are a mix of commercial and institutional building types (offices, community centers, libraries, museums,...). The average fossil fuel share of the buildings represented is very close to the average value in the CEUD, confirming that the selection of buildings is a fairly representative subset of the stock. Only a small percentage has a share of fossil fuel that falls around the average. Some of the buildings are fully electrified and use no fossil fuels at all. For those buildings that do use fossil fuels, there is a large variation in the share they

[4]The fossil fuels used in buildings are principally natural gas and fuel oil, but also propane and coal

represent, but in many cases they are the dominant energy source.[5] This variety of energy sources should be incorporated correctly into the models if they are to reflect consumption patterns of real buildings.

Table 3.5 The share of secondary energy use that consists of fossil fuels in 2019 for a sample of activity types [1]

Activity Type	Fossil Fuels [%]
Retail	0.447
Offices	0.287
Education Services	0.461

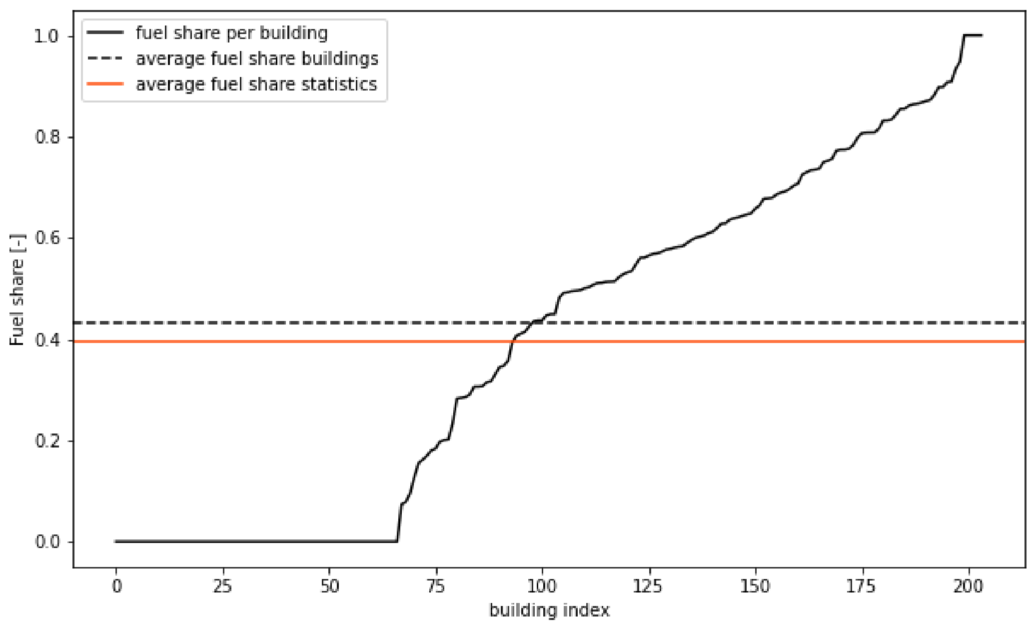


Figure 3.8 The percentage of a buildings energy use that constitutes fuel, for buildings managed by the city of Montréal.

Trends in Quebec school buildings

If we look at the share of fuel use in schools in particular, as shown in figure 3.9, we can identify similar trends, although there is a more gradual transition and thus a larger variety in

[5]Note that some buildings presented on this figure use only fossil fuels and no electricity, which would never be the case in reality. The data presented includes buildings with shared meters. Because it is not possible to distinguish the individual buildings' consumption when meters are shared, their consumption is combined and represented together. It is possible that for some buildings with shared meters a link could not be made and part of the consumption is missing.

the share of fuel used. This could be linked to a more decentralized approach to heating than in larger institutional/commercial buildings. As mentioned before, many school buildings have undergone some form of renovations. These renovations often involve only a portion of the school; an annex is constructed or an HVAC systems partially replaced. Many buildings will thus be equipped with multiple systems, resulting different combinations of equipment, possibly using different energy sources. The HVAC systems in particular will be discussed futher below. First the general energy consumption of the school building stock will be elaborated.

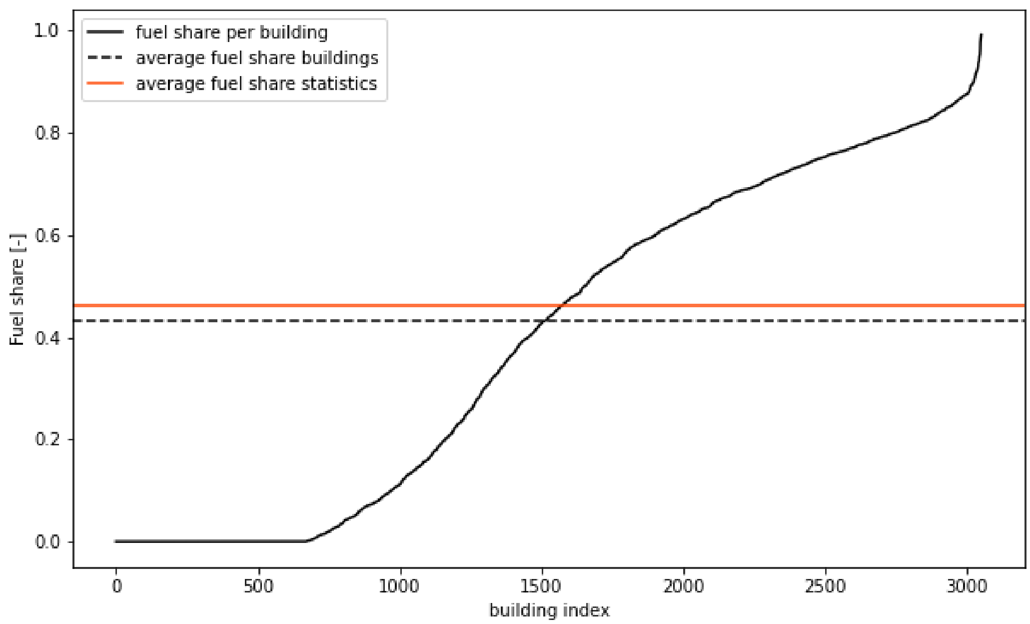


Figure 3.9 The percentage of a school buildings energy use that constitutes of natural gas [3]

Figure 3.10 shows the spread of the total energy consumption of schools (pre-, primary and secondary schools) [3] in function of the surface area. A regression of the first order is done to obtain an estimate of the average energy use intensity (EUI), resulting in a value of 0.66 GJ/m^2.

The energy use intensity (EUI) of individual schools in Quebec is shown on figure 3.11. The median of the EUI is 0.519 GJ/m^2. There is considerable variation in the EUI, looking at the school building stock as a whole. These variations can stem from a multitude of differences in building characteristics such as differences in building envelope, space types, but also HVAC systems. While a prototype model captures average characteristics, it could be necessary to represent variations in certain characteristics to better approximate the energy profiles of real buildings. We can assume that space types such as kitchens, heavy duty workshops and

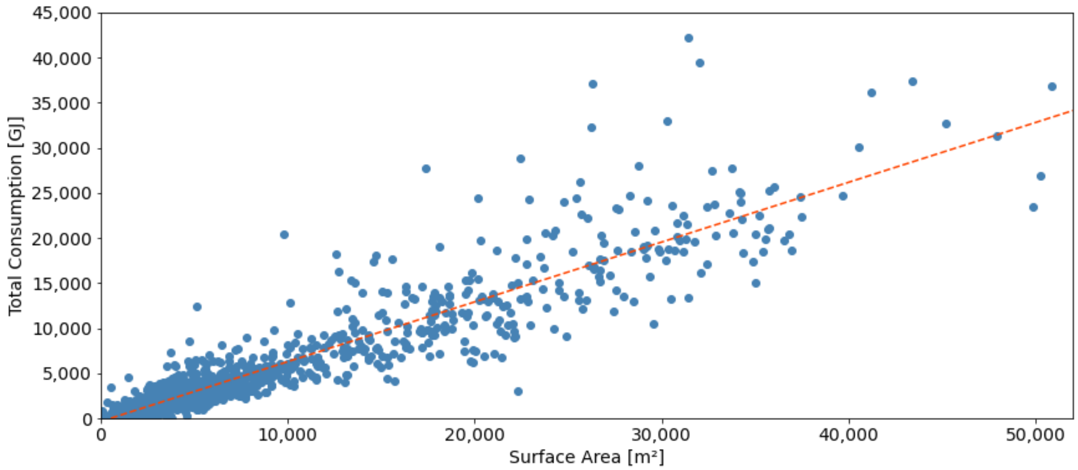


Figure 3.10 The total energy consumption of school buildings (pre-, primary and secondary schools) in function of the total floor area

swimming pools will directly impact the average EUI of a school because of their inherently high energy requirements.

Figure 3.12 confirms this trend in real consumption data. A similar impact can bee seen for the categories of HVAC systems. The figure shows boxplots of the EUI of buildings grouped by their respective category. The categories are aggregated by fuel source, space types and HVAC systems respectively in order to obtain a more significant set of buildings. Some of the individual categories are only represented by a single, or a handful of buildings, making the comparison of statistics invalid. The aggregation of the codes into larger categories does introduce a bias into the statistics, since there are tendencies of co-occurrence of characteristics. Buildings with a cooling system for example are more likely to also have heavy-use spaces (Type 1 and Type 2), making it harder to distinguish the effects of the presence of cooling itself. For completeness, the boxplots of individual categories is included and shown in figure 3.13. The number of buildings for the individual classifications is shown in figure 3.14.

Peak electricity demand is also given in the metered energy consumption data. Before using this data, some entries were removed from the selection because of incoherence in the data. Points with a peak registered as 0 kW have been removed. Then the Load Factor (LF) was calculated for all buildings—the load factor is the ratio between the average load and the maximum theoretical load (peak load multiplied by the period length). Buildings with a load factor above 1 were discarded as well[6].

[6]Even though load factors close to 1 are also likely to be erroneous, there is no cut-off value for which

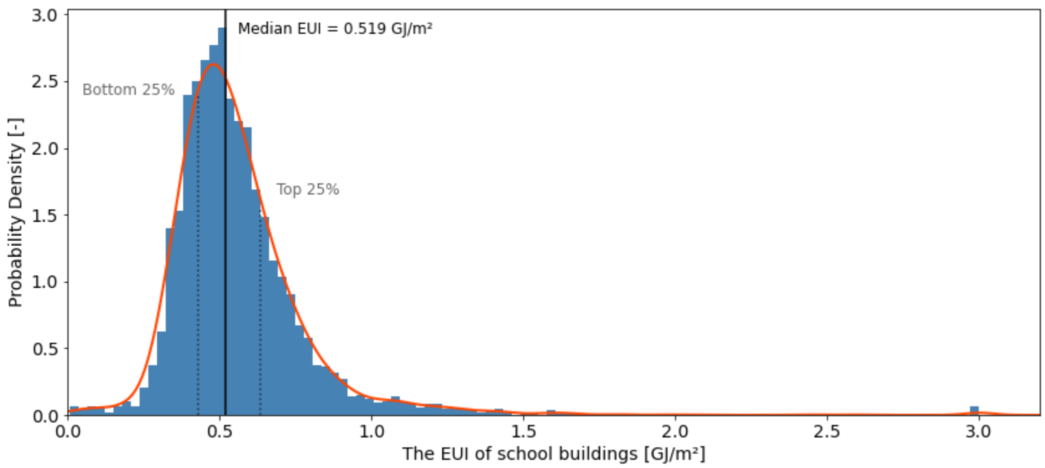


Figure 3.11 The probability distribution of the EUI of school buildings (pre-, primary and secondary schools) based on the energy consumption and floor area of 3079 schools. EUI values above 3 GJ/m² have been clipped for readability of the graph.

On figure 3.15a the peak electric demand is plotted against the total surface area. This is done only for schools which do not use any other energy sources besides electricity. The data shows the correlation between the electricity peak and a school's surface area. The trend derived corresponds to an average peak consumption of 0.054 kW/m².

Figure 3.15b shows the spread of the peak electricity demand per square meter for the same group of buildings. The median and mean are 0.050 kW/m² and 0.060 kW/m² respectively. The outliers have been removed for readability of the graph, but go up to 0.7 kW/m².

an LF can be assumed "too high to be realistic". Only a very small fraction of buildings has an LF in this "suspicious" high range however, meaning they will not impact the general statistics.

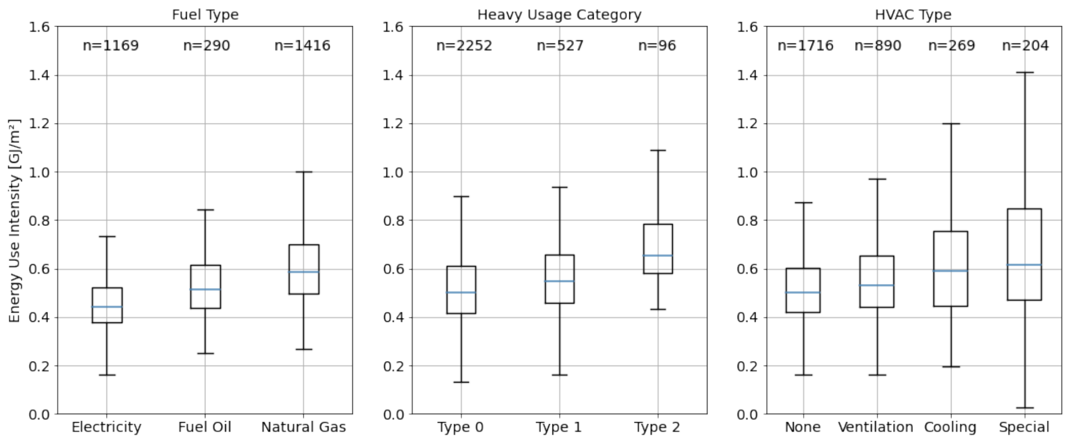


Figure 3.12 The EUI for schools grouped by the fuel source, heavy use category and HVAC types

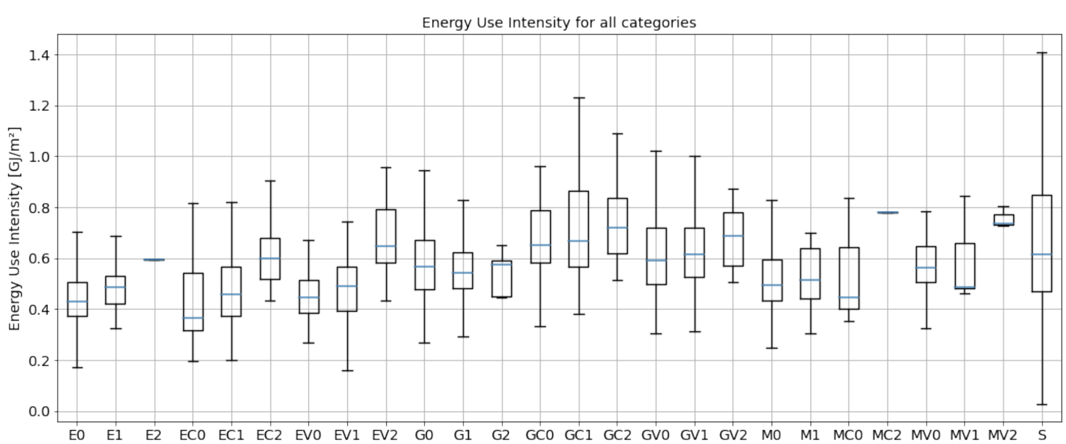


Figure 3.13 The EUI for schools for each category found in the database

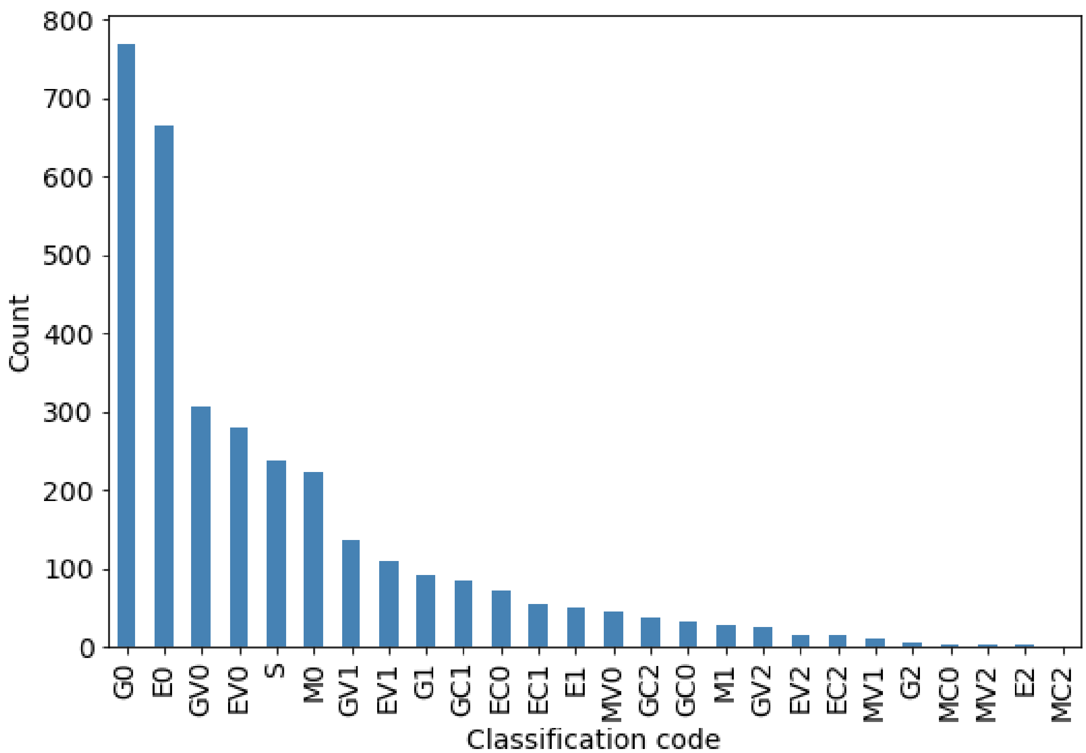
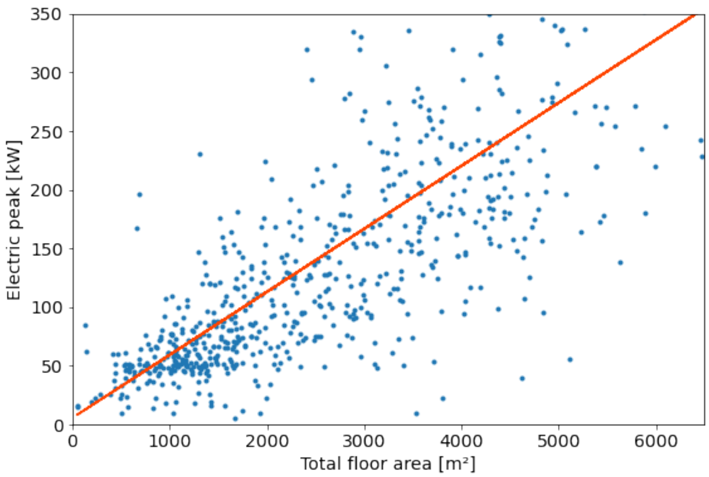
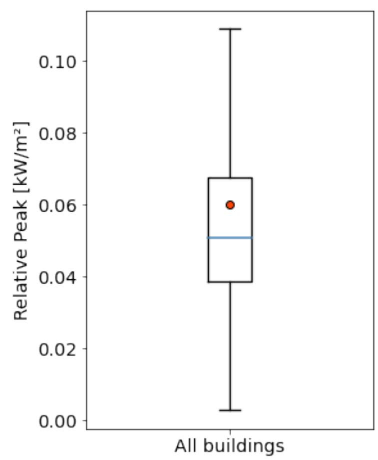


Figure 3.14 The number of buildings for each category found in the database



(a)



(b)

Figure 3.15 on the left, a scatter plot showing the relation between the peak electricity demand and the total floor area, for all schools using no other energy sources than electricity. On the right a boxplot showing the spread of relative peak electricity demand for the same selection of schools (n=676)

3.4.2 HVAC systems

For the study on the modeling of HVAC systems, a global picture is made of the most common HVAC types found in school buildings. The data presented earlier has already shown how there is a variety in fuel sources used, and whether buildings are mechanically ventilated and/or actively cooled or not. Using the treated survey data [45], a more detailed characterization of HVAC systems is possible, which will be done in this section.

The data classifies HVAC systems with regard to three main factors. In a first instance, the central equipment is identified. Buildings either have a central boiler and/or chiller, or they do not. A second categorization identifies whether a building has active cooling or not. If a building has a chiller for central cooling, this implies the presence of active cooling. The index thus allows distinguishing buildings that use decentralized cooling with Direct Expansion (DX) units. A third categorization is done on the type of ventilation. Four categories exist: buildings without mechanical ventilation, buildings ventilated with 100% outdoor air, ventilation with recirculation and dual-duct ventilation. The categorization factors and possible categories are summarized in figure 3.16.

The sample size for this data is over 800 buildings. For the purpose of this study, the data is used to identify common configurations of HVAC system and inform model inputs.

Most buildings have no ventilation system and operate either with a central boiler, implying a system with hydronic baseboards or radiators, or no central systems, implying the presence of electric baseboards in zones.

For the study on HVAC systems, the three ventilation types will be modeled using a central boiler for heating. According to the survey data [45], cooling is almost exclusively present in schools equipped with a central ventilation system. This means that it is the central air which is conditioned through a cooling coil, rather than decentralized units placed directly into spaces [7]. While both chillers and direct expansion (DX) units are commonly used, only DX-units are modeled to focus on the impact of the cooling demand.

The modeling of the systems is detailed in section 4.2, and simulation results will be discussed in detail in section 5.3.

In addition to the categories presented here, the survey data [45] presents some additional information, which is not presented here but will be discussed in Chapter 4 when used to define the prototype building model.

[7] It is possible that with the rising temperatures in summer, more decentralized units have been installed to condition specific zones, but because of the lack of data to support this hypothesis, these will not be considered here.

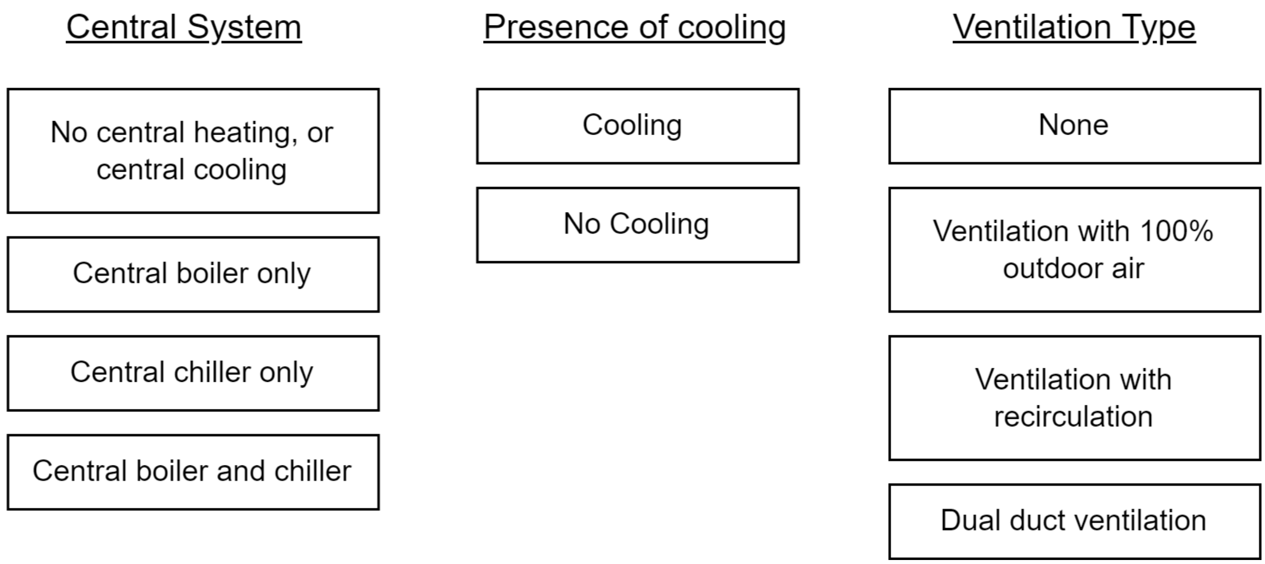


Figure 3.16 The classifications of HVAC systems

3.5 Differences with a typical U.S. primary school

Many UBEM and building stock studies in North America use of the models made available by the US-DOE [11]. As mentioned before, these models are also used for studies on Canadian regions.

Now that the school buildings in Quebec have been characterized, it is interesting to show some fundamental differences with what is modeled in the U.S.-DOE the prototypical primary school.

Most information in the U.S.-DOE Primary School reference building and prototype building models has been taken from a study of K-12 schools by Pless et al [32]. The report presents information from the Commercial Buildings Energy Consumption Survey (CBECS) and concludes on typical characteristics used as model inputs. The information presented brings to light the differences in characteristics of U.S. schools compared to schools in Quebec.

Some illustrating examples are given: the building form, the access to natural lighting and the presence of active cooling.

Building form Based on a study of built form, Pless et al [32] decided that a common building shape is a 'fingered' shape. The study on geometry in Quebec, on the other hand, shows that over half of the school buildings are rectangular in shape. The average floor area was reported to be over 7000 m^2, which is significantly larger than the floor area of most schools in Quebec.

Daylighting The survey shows that for most buildings, the window-to-wall ratios less than 25%. On top of that, less than 10% of their floor area has access to daylighting. In Quebec we find the exact opposite where school buildings built in the era of high construction rate focused on building efficient building with high access to natural light and natural ventilation, having large window-to-wall ratios and resulting in the rectangular shapes with relatively high aspect ratios.

Active cooling The survey shows that almost all schools have active cooling in most of the school building, whereas in Quebec less than 10% of the school buildings have a significant portion of their floor area actively cooled.

These are just a few examples of how different the buildings found in Quebec are from those represented by the DOE archetypes. This is why a proper understanding of the building stock is important, so it can be reflected by the models used in studies. A few of these inputs are easily changed in the model (such as removing the cooling system), but others are more fundamental, such as the building shape.

3.6 Conclusion

This chapter presented an overview of architectural and energy use data available on Quebec school, and the analysis that was performed in order to inform the design of the prototype model presented in the next chapter. This study focuses on the differences resulting from different HVAC system configurations, so it was decided to define a "typical" prototype building for other aspects: the selected building is a primary school (the most frequent educational building type), with a rectangular shape, a flat roof, and other geometrical characteristics taken from most frequently found configurations. The analysis has also highlighted that energy use, and the distribution between electricity and fossil fuels, cannot be represented by an "average" building, which was one of the drivers for this thesis. The most frequent HVAC system types were identified, and will be implemented in the model described in the next chapter. Finally, a comparison with the school archetype typically used in North America [11] has shown that some basic assumption from that archetype are not applicable in Quebec, justifying the effort invested in developing a prototype model specific to the Quebec context.

CHAPTER 4 MODEL DEVELOPMENT

4.1 Developing the base case model

The base model is made to be representative of a "typical" school building. It is not modeled after one school in particular but includes values of parameters and configurations that are most commonly seen. Statistical consumption data will be used to confirm the general validity of the model. In the following subsections, the modeling parameters will be elaborated.

4.1.1 Geometry

As discussed in section 3.3, most schools in Quebec have a rectangular shape. The number of floors together with the footprint surface area determine the total floor area. The model has a footprint area of 1000 m^2 and two floors. There is a gym present in the building which extends over two floors, reducing the total floor area of the building to 1640 m^2, which falls in the bin of a "typical" school size. The aspect ratio of the footprint is 2.5.

Since the schools constructed during the 'education boom'-period were favoring natural lighting and natural ventilation, the window-to-wall ratio is high. Sources [45] [5] document the fenestration area as a proportion to the total floor are of the building (window-to-floor-area ratio), instead of by the commonly used window-to-wall ratio. For the schools favoring natural lighting and ventilation, these ratios lie between 20% and 25%. The windows of the base model are sized to obtain a window-to-floor-area ratio of 21%. This corresponds to a window-to-wall ratio of 41% for this geometry. The resulting geometry is shown in figure 4.1.

The model does not take into account any shading from exterior obstructions or shading devices in the building, or the impact of dividers in the windows.

4.1.2 Zoning

Figure 4.2 shows the zones modeled on each floor. The presence of the zone types is based on the survey data [45]; the sizes and placement within the building are based on guidelines from the Quebec government [49] and studies done on school architecture [5] [2].

Survey data shows that schools of this size dedicate the majority of their surface area to classrooms (45-60%). Corridors take on average around 15-20% and a gymnasium takes up on average 23% of the total floor area. While schools should attribute at least 6-8% of their surface are to complementary services (library, offices, etc.), in reality this varies between 4%

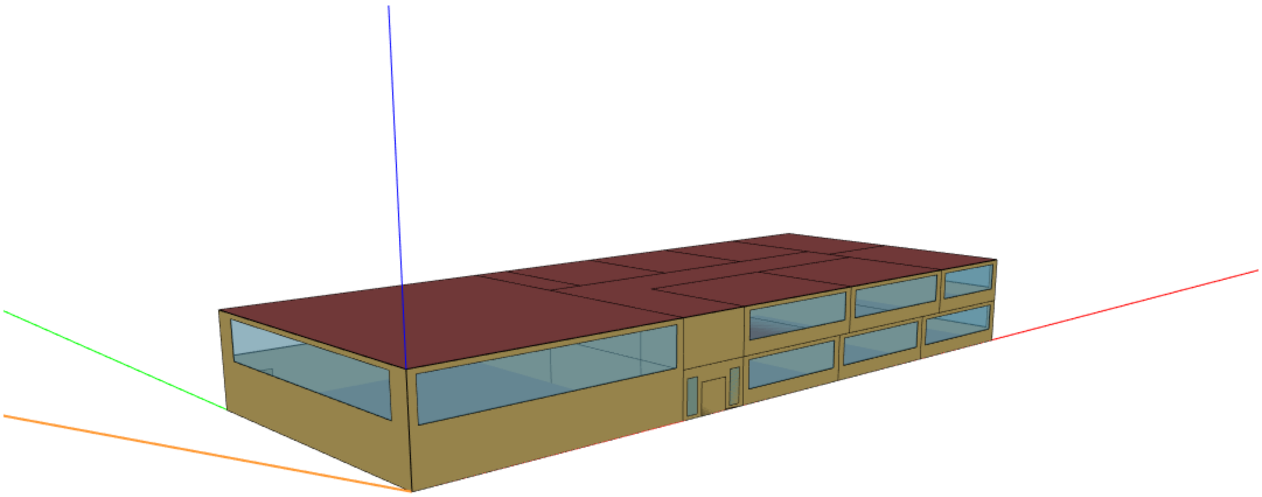


Figure 4.1 The geometry of the model created in OpenStudio

and 9%. The cafeteria, while not always present, takes up 5% to 10% when it is. Storage and mechanical rooms cover about 5% of the surface area [45] [5].

The size of a classroom should be at least 50-72 m^2 for primary education to accommodate 18-29 students. Spaces allocated for physical education should be at least 360 m^2 [49]. On average, a school building has 4-8 m^2 surface area per student. The area per occupant in classrooms is 3.4 m^2/student, on average [5].

Based on this information, the zone types in the model have been attributed to the physical spaces as shown in figure 4.3. The resulting model has 10 classrooms of 69.6 m^2 on average, accommodating a total of 205 students.

Merging of thermal zones is often done to reduce the complexity of energy models. The guidelines for this process are discussed in ASHRAE 90.1 [50]. For the model considered here, the zones which could be merged are limited because of the small size of the building. For the purpose of this study, and to maintain accuracy [7], the thermal zones of the model coincide with the individual spaces.

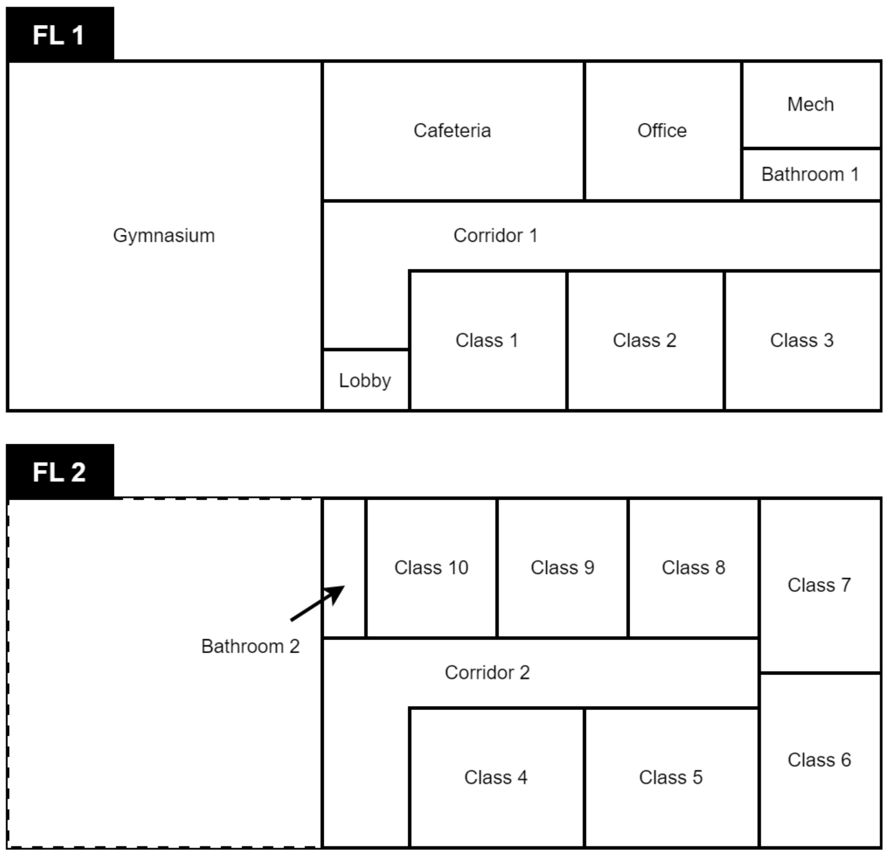


Figure 4.2 The floor plan of the geometry

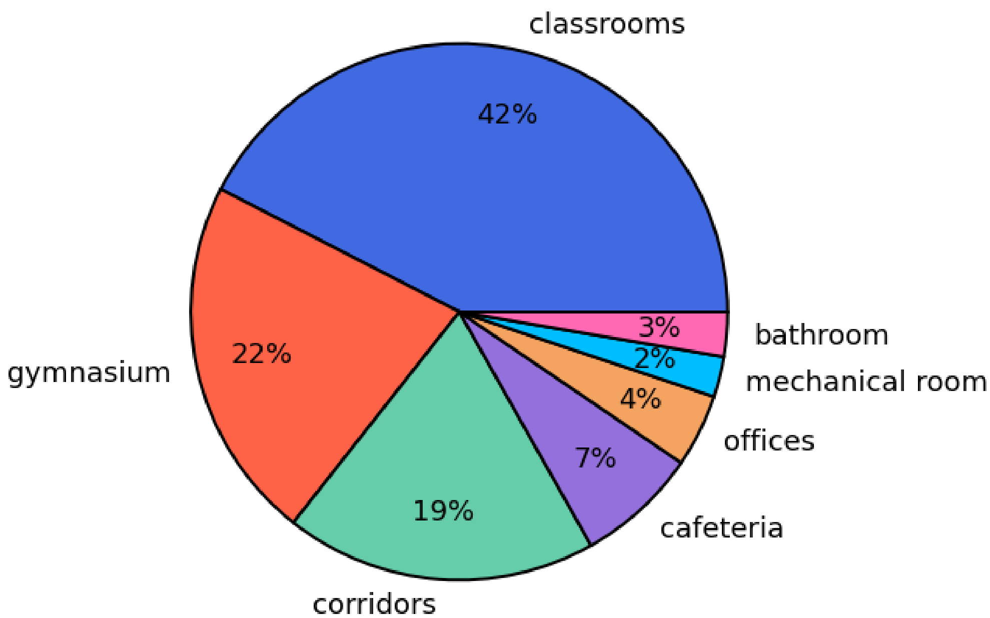


Figure 4.3 The surface area percentage for each zone type

4.1.3 Constructions

The construction materials used in schools are documented in [5] and show that wood, concrete and steel are the main construction materials throughout the years. Different periods of construction showed dominance of different materials. During the period of high construction (1945-1965), mainly wood and concrete were used. For this model, the material used is assumed to be concrete. Data shows that for schools constructed in concrete, the facade is often made of brick [5]. Data presented in [45] gives us estimates of U-values of walls, floors and roofs. Until 1980, slab-on-ground constructions were generally not insulated [45]. SIMEB [51] contains a database of constructions of different types, allowing us to implement different layers according to the construction materials used. The resulting constructions are shown in table 4.1.

Table 4.1 Materials and thermal transmittance of the constructions used in the model

Construction	Description	U-value [W/m²K]
Ground Floor	Heavy weight concrete (30 cm), Tile flooring	1.907
External wall	Face brick (10 cm), Air layer (2 cm), Polystyrene insulation (2.6 cm), Gypsum (1.5 cm)	0.811
Interior wall	Gypsum (1.27 cm), Gypsum (1.27 cm)	2.511
Interior ceiling/ floor	Heavy weight concrete (10 cm), Tile flooring	2.097
Roof	Roof Gravel (1,2 cm), Polystyrene insulation (11.2 cm), Light weight concrete (5,1 cm)	0.284
Glazing	SHGC=0.41, (Simplified model)	3.52
Door	(Thermal resistance only)	1.598

4.1.4 Infiltration

The infiltration is modeled with the `ZoneInfiltration:DesignFlowRate` object. Using equation 4.1, a user defined design flow rate is corrected for influences by indoor and outdoor temperature, and wind speed. The coefficients A, B, C and D in equation 4.1 are set to

0, 0, 0.224 and 0, respectively, as recommended for modeling infiltration in the DOE-2 program [16]. The value of I_{design} is adjusted to obtain an average infiltration flow rate (I) of 0.25 L/(s.m^2), corresponding to the (constant) value set for infiltration in SIMEB [51]. This adjustment is specific to the weather file (CWEC file for McTavish), and results in $I_{design} = 1.83$ L/(s m^2). In comparison, the value of I_{design} in the pre- and post-1980 primary school in the commercial reference buildings [11] is set to 1.133 L/(s m^2) but the coefficients A, B, C and D in equation 4.1 are set to 1, 0, 0, 0 respectively. Gowri et al. [52], on the other hand, recommend to use a value of $I_{design} = 1.024$ L/(s m^2) with the DOE-2 coefficients (A=B=D=0, C=0.224).

$$I = (I_{design})(F_{schedule})[A + B\,|T_{zone} - T_{amb}| + C(V_{wind}) + D(V_{wind})^2] \tag{4.1}$$

Additional infiltration is added to the lobby to account for the airflow resulting from the opening of the main entrance door. The infiltration is scheduled at the starting and ending hours of school days. The value of the infiltration flow rate is taken from the DOE primary school prototype building [20]. The original source of this information could not be confirmed, but a different study on the modeling of air flows in public buildings show similar rates of air flow [53].

4.1.5 Natural ventilation

Since many schools do not have a mechanical ventilation system [3] [45], to maintain a certain level of air quality in the classrooms, spaces are ventilated through the opening of windows. The level of natural ventilation in a classroom depends primarily on decisions made by the occupants (opening and closing of windows, and the degree thereof), which adds complexity to the way it should be modeled. In order to come to an appropriate way to model natural ventilation, the following questions are answered:

1. What modeling options within EnergyPlus exist and which are the most appropriate to implement natural ventilation?
2. What impact does the control strategy of the opening of windows have on the simulation results?
3. How important is it to include natural ventilation in a BEM when no mechanical ventilation systems are present?

EnergyPlus Object: Energy Plus allows different methods of modeling natural ventilation. Each of them simulates an airflow which depends on indoor and outdoor conditions, with varying levels of complexity. The most simplified method uses the ventilation design flow object. The object allows including an air flow rate based on a design flow rate with variation induced by indoor and outdoor temperature and the wind speed, where each of the coefficients influencing the importance of respective variables are customizable. It does not take the direction of wind into account. The most suitable approach was therefore found to be the one using the `ZoneVentilation:WindandStackOpenArea`. This method includes influences of wind speed and thermal stack effect, as well as effects of the direction of the wind with respect to the window opening. A more detailed approach is possible using an air flow network model, which allows including more details on the shape and positioning of the window opening, and uses wind pressure coefficients to calculate the resulting ventilation, thus including the impact of the shape of the building on the air flow. This method however requires information that is not available without detailed studies, and does not give more accurate results unless these data are well known and defined in the model.

The `ZoneVentilation:WindandStackOpenArea` object is implemented for all zones with operable windows (classrooms and office). The opening area of the windows are set at 2.56 m^2 per zone, according to the guidelines in the National Building Code [54]. The native algorithm will consider the windows to be open when the zone is at a user-defined minimum temperature, which is set to the zone set-point temperature. Additionally a user can add limits for outdoor conditions outside of which the windows can not be open. The limits are set to only be opened when the outdoor temperature is within the following limits: [-13°C;30°C]. Following this control, if the outdoor temperature falls within the pre-set boundaries and if the zone temperature is at least at set-point temperature, windows will be opened. They will be closed again when these conditions are no longer met.

Control strategy: This simple control strategy does not take into account how a real occupant would manipulate windows. Firstly, when an occupant decide to open a window, it is rare that all operable windows are opened fully at the same time. Secondly, there is always a trigger to why an occupant will open a window; this could be for thermal comfort, air quality or other reasons [55]. To reflect this behavior better, the zone ventilation object is complemented with ad-hoc control strategies.

Based on the information presented in the report by Mercier [55] on occupant behavior in Quebec classrooms, the following control aspects are adapted in the control strategy:

Instead of allowing windows to be opened equally during the day (always fully open), there is a schedule applied all year around and allows the windows to be opened by different fractions. The schedule follows times where air quality is most likely to be degraded (the hour before noon and before the end of the day) and students would feel the need to get some fresh air.

Additionally, a control is added that allows opening the windows to larger fractions when outdoor temperatures are mild and the ventilation could serve as natural cooling.

Figure 4.4 shows the impact on ventilation rates during a winter and summer day of the adapted control strategy with respect to the basic control strategy. The application reduced opening fractions prevents windows from being opened too much in winter, while the additional control ensures that in winter the windows can still be opened fully to allow natural cooling.

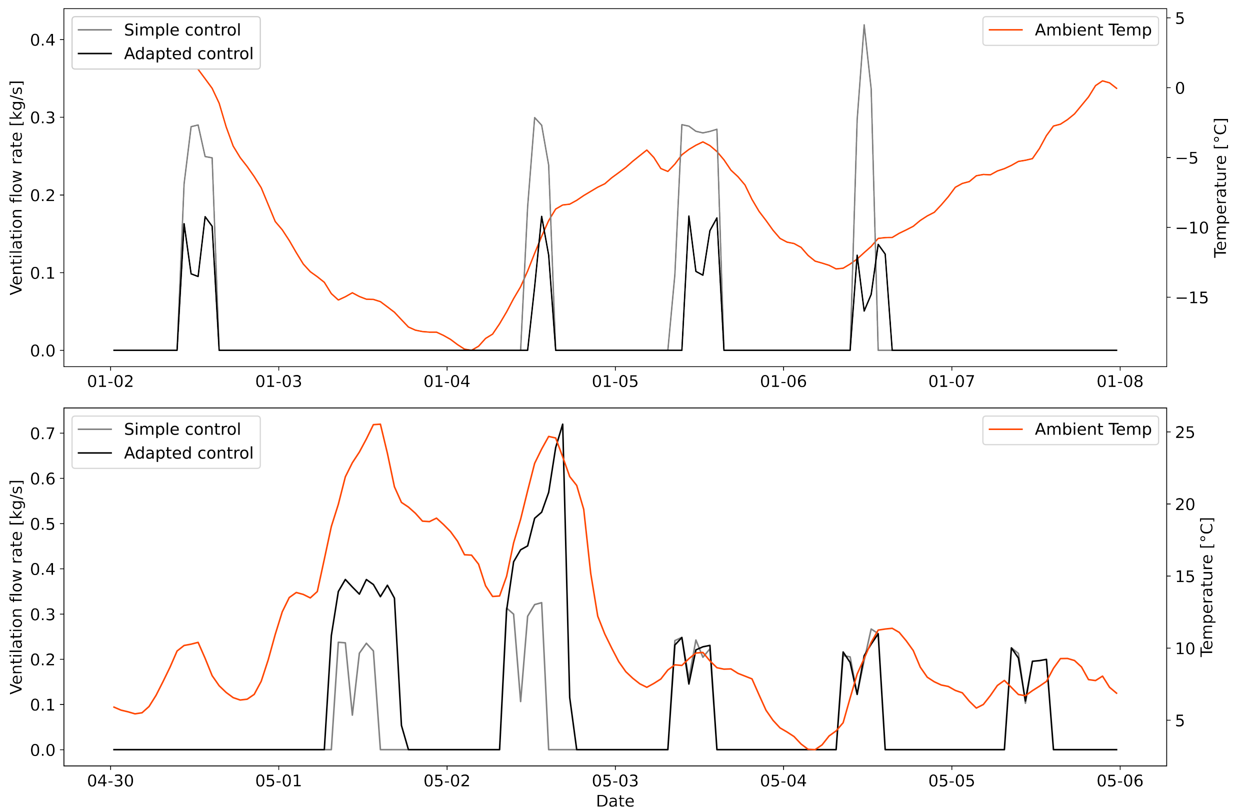


Figure 4.4 The ventilation flow rates for the native (simple) control of natural ventilation and for the adapted control. The top figure shows the reductions in flow rate in winter because of the application of the fractional schedule. The bottom figure shows how the additional control allows windows to be opened more on a summer day.

The self-implemented control remains an *attempt* to mimic the behavior documented in the paper by Mercier [55]. Validation of the model's reaction to changes in the environment against detailed data would be beneficial but has not been possible. However, considering the importance of including natural ventilation in the model and the oversimplification in the native controls, the adapted control is considered to be an improvement, and sufficient for the study at hand. One should keep in mind, however, that the impact on the profile of the heating load largely depends on the timing and degree to which the windows are opened in winter. This should be kept in mind when interpreting the simulation results.

Comparison to model without natural ventilation: A comparison between the final model including natural ventilation and the model without any ventilation shows that there is mainly an impact on the zone temperature in spring and summer, since the ventilation serves natural cooling. But there is also a difference of 8% on heating energy consumption, since the natural ventilation is also used in winter to have circulation of fresh air, resulting in a larger heating load.

4.1.6 Service hot water

For lack of more detailed data on the hot water usage in Quebec schools specifically, the model assumes values suggested by The ASHRAE Handbook of HVAC applications (2019) [56]. A daily usage of 2.6 L/student is implemented with a fractional schedule as per the average hourly flow profile for elementary schools presented.

The water heater is assumed to be electric. There is no explicit data available on this, but the meter consumption data [3] indicates that it is common. Out of all the schools which have electricity as their main energy source for heating (labeled with **'E'**), 53% have no additional consumption of fossil fuels, meaning they use *exclusively* electricity for all end-uses. The presence of electric water heaters could be higher, since the fossil fuel use registered for these schools could be used for other end-uses.

4.1.7 Internal gains and schedules

The internal gains come from occupants, lights and appliances present in zones. The design values used as an input in the EnegyPlus model are summarized in table 4.2. The schedules applied to these values are shown in figure 4.5.

The occupancy density, expressed as the floor space available per person [m^2/person], of the classroom is based on [5]. The schedule applied to has been taken from SIMEB [51]. This schedule is applicable during weekdays. During weekends and summer holidays, the school is assumed unoccupied, based on survey data which shows that most schools operate 40 hours per week and 10 months per year.

The lighting intensity was been adapted from the survey data [45]. The survey concluded an average value of 13.5 W/m^2. This value has been reduced, considering the advances in lighting technology since the survey was performed, assuming that lights are systematically being replaced as they reach their end of life, or as energy efficiency measures. The average lighting intensity for the model is 10.3 W/m². The value varies depending on the zone type, as presented in table 4.2. The lighting schedule is taken from SIMEB [51].

The equipment intensity was set to 11 W/m² in classrooms, following a study done on plug loads in the U.S. [57] and values presented in [32] based on survey data. The schedule is again taken from SIMEB [51], except that for unoccupied hours, a larger stand-by load is assumed [21].

The schedule values for all internal gains are set to their minimum values during the weekend and summer holidays, considering the fact that the school is assumed unoccupied at these times.

Table 4.2 The design values for the occupancy, lighting and plug load gains

Occupancy classroom [m²/person]	3.4
Lighting density classroom [W/m²]	14.35
Lighting density other spaces [W/m²]	8
Plug Load density classroom [W/m²]	11

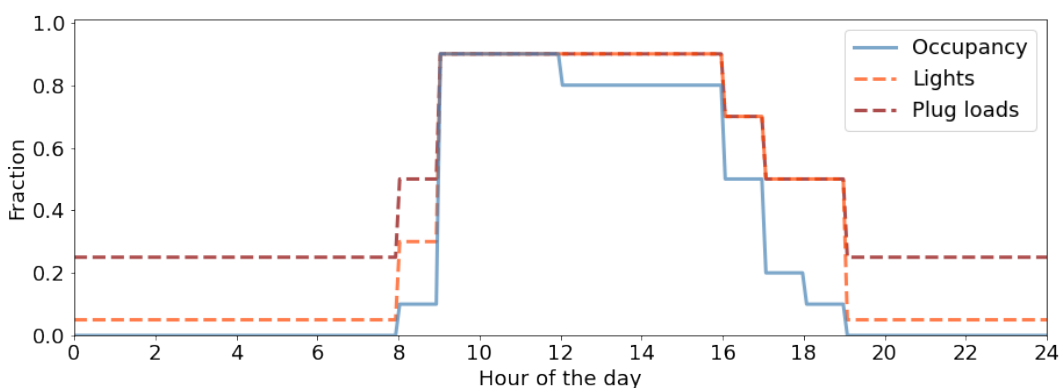


Figure 4.5 Occupancy, lights and plug loads schedules

Daylighting controls

As mentioned earlier, the access to natural lighting is a key characteristics of a typical school in Quebec. Anecdotal evidence suggests that automatic daylight control in schools is unlikely, but the access to natural lighting will still have an impact through occupant behavior.

The study done on occupant behavior in a classroom in Quebec documented the turning on and off of lights in classrooms [55]. The study shows that while actively using a classroom, the action most often taken is the turning ON of lights when the room is too dark, occupants are less likely to turn OFF lights when daylighting is sufficient.

EnergyPlus allows implementing lighting controls that account for occupant decisions by factoring in probability. The user can define the probability with which lights will be turned down if daylighting is sufficient (according to the user-specified level of illuminance), otherwise the lighting will be assumed to be set at the higher level. This translates into a control where there is a chance that occupants will turn off the light when there is enough daylighting, but do not always do so. The lights will always be turned back on when the daylighting levels drop below the user-defined treshold.

Daylighting has been implemented with an ON/OFF control, where the lights are turned OFF with a 70% chance if at a depth of 2/3rds of the zone the illuminance level is above 300 lux. This level is recommended by many international standards and often used in assessing daylight autonomy [58].

4.1.8 Baseline HVAC system

Following the conclusions from section 3.4, each zone is equipped with electric baseboards. The bathrooms, cafeteria and gymnasium are also equipped with exhaust fans.

Heating equipment

The baseboards are modeled with the `ZoneHVAC:Baseboard:RadiantConvective:Electric` object. 80 % of the energy is added to the zone through convection. The remaining 20% of the energy is radiated onto the surfaces and people in the zone.

Little information is known about the capacity of these types of equipment, but from several detailed studies done on the replacement of heating systems in schools [42] [43], it is found that heating equipment is generally oversized. For this reason, the heating equipment of the model will be autosized in EnergyPlus, to allow the equipment to meet zone demand.

Heating setpoint

The heating setpoint is set at 22°C [51]. A setback is implemented since it is present in the majority of schools [45].

Exhaust fans

Exhaust fans are assumed to be installed in the bathrooms, cafeteria and gymnasium to remove odours and moisture. In the bathrooms, the extraction of air is assumed to be compensated by infiltration. For the cafeteria and gymnasium, an inlet of outdoor air is provided. This air is preheated by an electric heating coil for neutral supply.

The extraction of air is in accordance to ANSI/ASHRAE Standard 62.1-2007 [59] and is active when the building is occupied.

4.2 HVAC system variations

The base model is adapted and to include different HVAC system configurations. The variations represent possible configurations in the school building stock, but not necessarily the ones that are the most dominant. The goal of this study is to assess the significance of the impact on simulation results, without directly connecting the variations to the building stock.

The main objective is assessing the impact of modeling the *conceptual* differences of systems. There is however also an aspect of *modeling choices* within the software which is also touched upon.

The different HVAC configurations discussed are divided into three main categories:

1. Without mechanical ventilation
2. With mechanical ventilation, no cooling
3. With mechanical ventilation and cooling

Different sub-variations of each category are implemented and discussed below.

4.2.1 Without mechanical ventilation

Most schools do not have centralized ventilation, which is why this is the configuration implemented for the base model. The base model uses electric baseboard heaters for space heating, but space heating could also be provided through hydronic radiators, with hot water coming from a central boiler.

The base model has an outdoor air unit for the gymnasium and cafeteria that assures the extraction of air and supplies outside air at neutral temperature. A variation is modeled with heat recovery on the exhaust air.

These two variations will be detailed in the following subsections.

The opening of windows remains implemented as discussed in section 4.1.5 for the models without mechanical ventilation.

Variation 1: Heat recovery on exhaust

Most heat recovery on exhaust in schools only recover sensible heat. A flat plate heat exchanger is thus added to the exhaust flow of the cafeteria and the gymnasium. It preheats the inlet air before going through the heating coil. The diagram of the outdoor air unit is shown in figure 4.6. The heat exchanger is modeled with a 76% efficiency at nominal air flow rate.

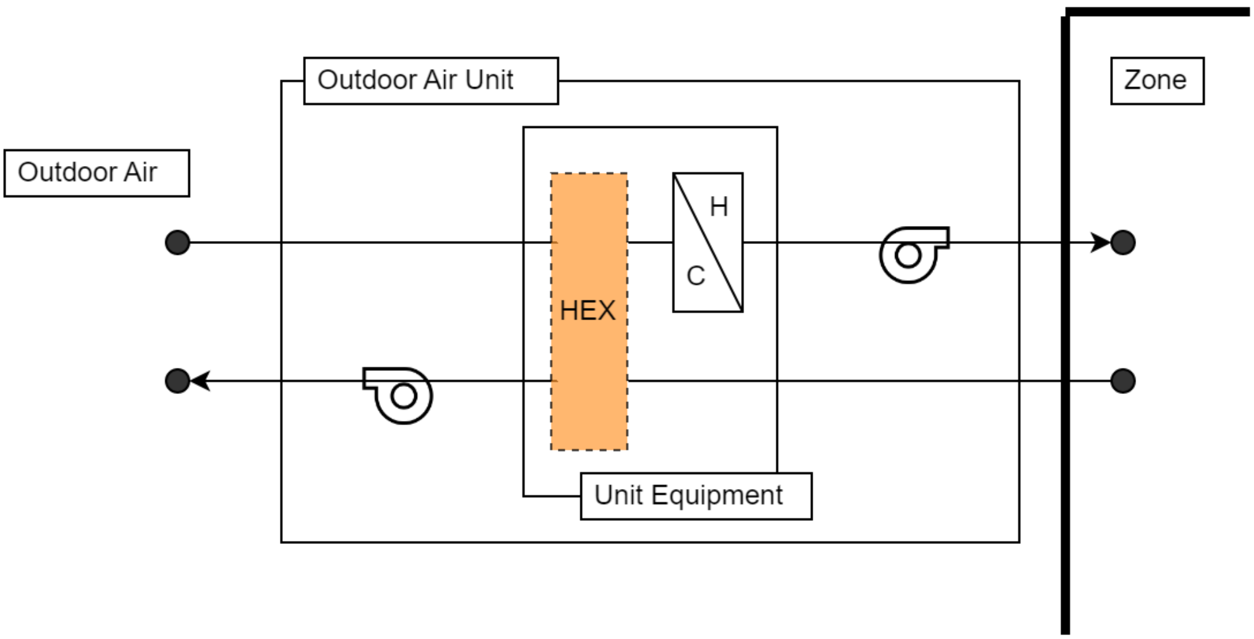


Figure 4.6 A diagram of the outdoor air unit with heat recovery on exhaust

Variation 2: Centralized hydronic heating

The electric baseboard heaters in all zones are replaced by hydronic baseboards with hot water provided by a central electric boiler.

The hydronic baseboards are modeled using the `ZoneHVAC:Baseboard:RadiantConvective:Water` object. Similarly to the electric baseboard, it allows specifying the fraction of convective and radiant energy, which are kept at 80% and 20% respectively. They also require the specification of a rated average water temperature, which is set at 58°C.

Figure 4.7 shows a diagram of the hot water loop that is modeled. An electric boiler is set to heat the water to 85°C, which is then circulated by a constant speed pump to the hydronic baseboards. The boiler is modeled with a constant efficiency of 100%. The baseboards, boiler and plant loop are autosized.

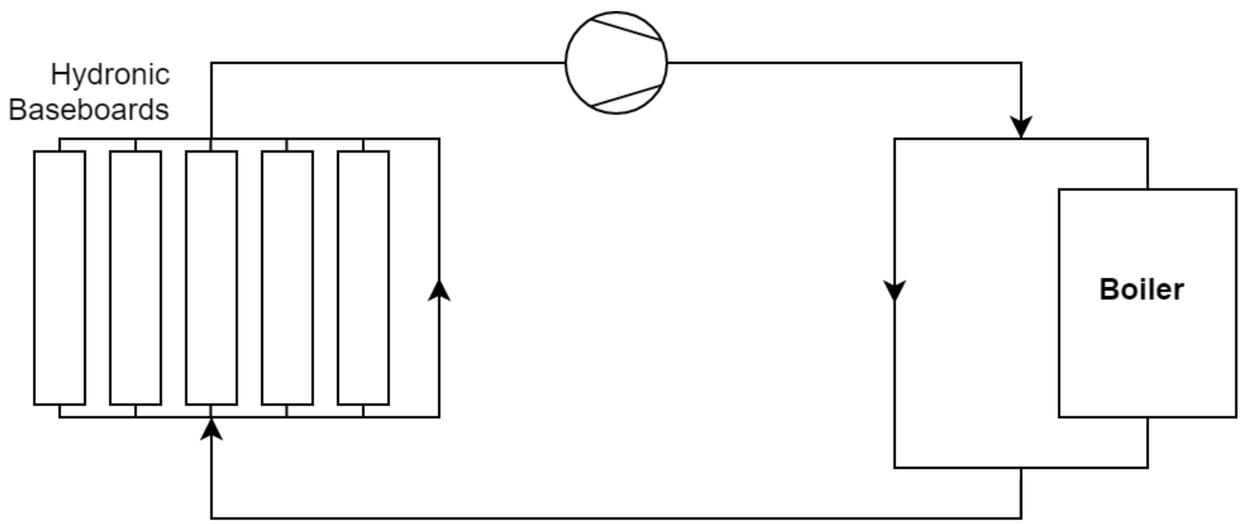


Figure 4.7 A schematic diagram of the hot water loop for hydronic baseboard heating

4.2.2 With mechanical ventilation, no cooling

The configurations with mechanical ventilation assume the same ventilation type for all zones, but are modeled with two separate air-loops; one supplying the gymnasium, cafeteria and bathrooms separately, because of the presence of exhaust fans and their impact on the air balance. The second air-loop serves the remaining zones.

Outdoor air requirements

For school buildings in Quebec the guidelines on outdoor air requirements are not precise. The reference guide (*Document de référence sur la qualité de l'air dans les établissements scolaires*) specifies a minimum supply of 2.4 L/s per occupant, but also notes that this may not be sufficient and comfort could be compromised. A value of 7.5 L/s is given as a recommendation. Because of the inconclusiveness of the guidelines, the provision of outdoor air in the models will follow national building code recommendations. The outdoor air requirements for each zone are in line with BNC 2015 (referring to ASHRAE 62-2001) and summarized in table 4.3.

Table 4.3 The outdoor air requirements specified for each zone type

Zone type	People Outdoor Air Rate [L/s.person]	Area Outdoor Air Rate [L/s.m^2]
Classroom	5	0.6
Offices	5	0.6
Gymnasium	10	0.9
Cafeteria[1]	1.9	0.3
Corridor	0	0.3

For all models with mechanical ventilation, natural ventilation has been removed. While the HVAC system is operating, infiltration is reduced to 25% of its nominal value [52].

The three variants discussed in section 3.4.2 are modeled. The modeling inputs are detailed below. They all specify the same outdoor air requirements and use components with the same ratings to focus the comparison on operational aspects. All components are autosized.

Diagrams of the systems are added to visually support the discussion of the layout and components. The diagrams also include a cooling coil, for the discussion on ventilation systems with cooling following in section 4.2.3.

Variation 1: Ventilation with recirculation

A diagram showing the system layout is shown in figure 4.8. On the right the air loop is represented with the central HVAC equipment. The air coming from the central air-loop is divided and sent to the air distribution units of the individual zones (two zones are shown on the diagram to illustrate this).

The two central air-loops of the building consist of the same components, except that the gymnasium, bathrooms and cafeteria also have an exhaust fan in each zone, assuring the extraction of odors and moisture (not shown on the diagram).

The ventilation system is responsible for maintaining zone comfort levels, there is no additional heating equipment in the zones. A central heating coil preheats the air to 13°C. To ensure that zones are kept at set-point temperature, the zone's constant volume air distribution units (CV ADU) are equipped with reheat coils (RH).

The circulation of air is imposed by a constant volume fan, most commonly present in school buildings (of this age and size) [45]. The ventilation system is set to follow occupancy, as this is predominantly the case [45], and goes into a night-cycle outside of occupied hours. Outside of occupied hours, the ventilation will be turned on systematically to maintain zones at set-point temperature. The system uses demand controlled ventilation to vary the outdoor air fraction and reduce the intake of outdoor air outside of occupancy hours. The fraction of outdoor air is controlled by the outdoor air unit. At night, a minimum outdoor air flow is maintained, proportional to the zone surface area, as specified in table 4.3.

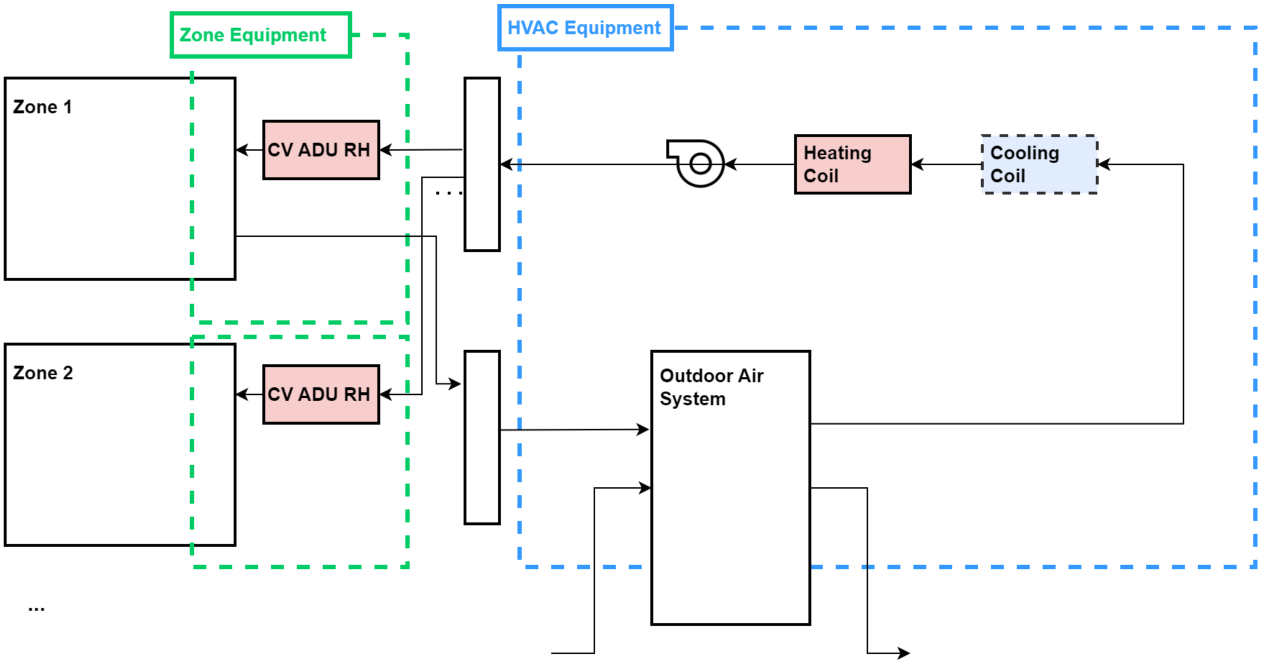


Figure 4.8 A schematic diagram of the ventilation system with recirculation

The heating coils are hot water coils, connected to a central loop with an electric boiler. the configuration is similar as in the diagram shown for hydronic baseboard heating, except that the water coils are connected on the demand side instead of baseboards. The operation of the water loop is equivalent and the components have the same ratings. This same configuration is used for the heating coils in all following models.

Variation 2: 100% outdoor air

A similar configuration exists where the ventilation system provides only outdoor air. In this case there is no recirculation of air, the outdoor air unit simply relieves the return air from the zones and supplies 100% outdoor air. The diagram is shown in figure 4.9.

The ventilation system is used solely to provide outdoor air into the zones. The air is not conditioned to meet each zone's thermal loads, but is supplied at a neutral temperature (18°C). A central heating coil heats the air to meet this setpoint. Additional zone equipment assures that zones are kept at their set-point temperature. The zone equipment installed are electric baseboards with the same specifications as those in the base model.

Since it is not the ventilation, but the electric baseboards that provide zone heating, there is no ventilation at night.

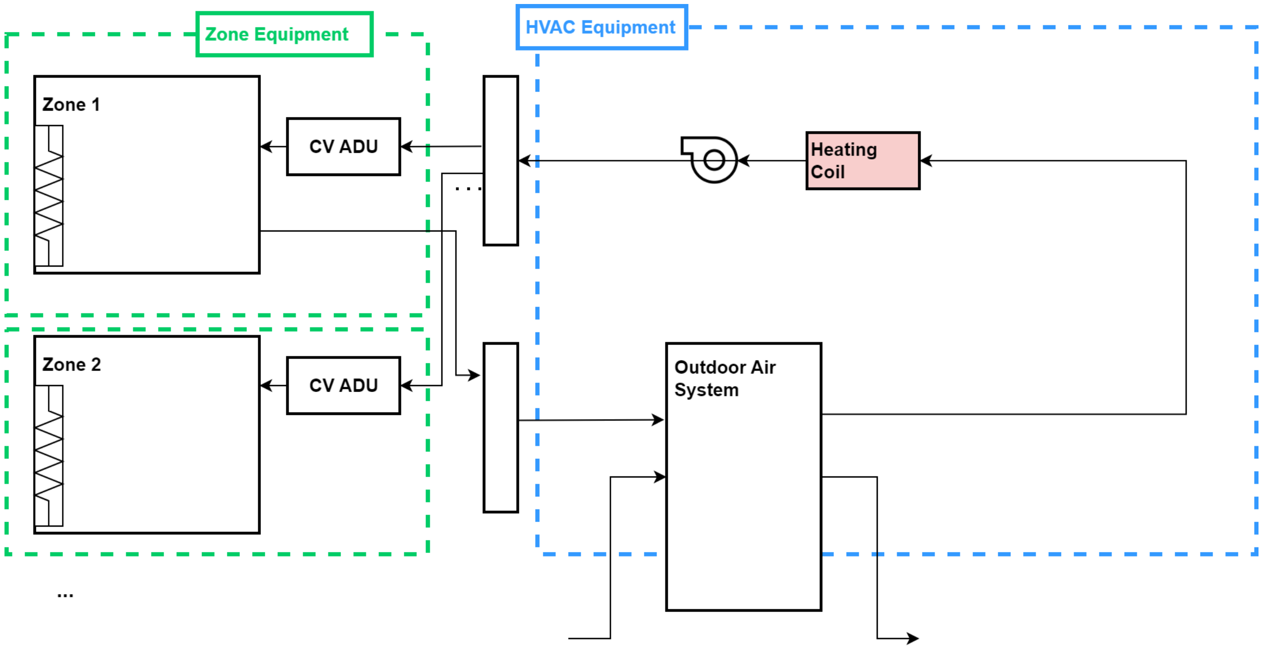


Figure 4.9 A schematic diagram of the ventilation system with 100% outdoor air

Variation 3: Dual-duct ventilation

A dual duct configuration provides a flow of cold air and a flow of hot air separately into a zone to meet the zone's thermal load. The total air flow going in to the zone is maintained constant, but the ratio of cold to hot air is varied to maintain zone temperature. Figure 4.10 show the system layout.

Data shows that some schools are equipped with a dual-duct system without any form of cooling equipment attached to it. In the current configuration, the outdoor air is added to the air stream before it is split up. One stream is then heated to meet the set-point of the hot air flow, while the "cold" air-stream remains unconditioned. Simulation showed however that the lack of conditioning of the cold air supply resulted in an increased airflow through the cold duct in an attempt to meet the zone's thermal load. Since it is not possible to mimic any real-life operation of this system because of the lack of information of the exact lay-out of such a system or the control strategy applied, the model is not included in the analysis.

In the following section, a cooling coil will be added to model the common dual-duct configuration.

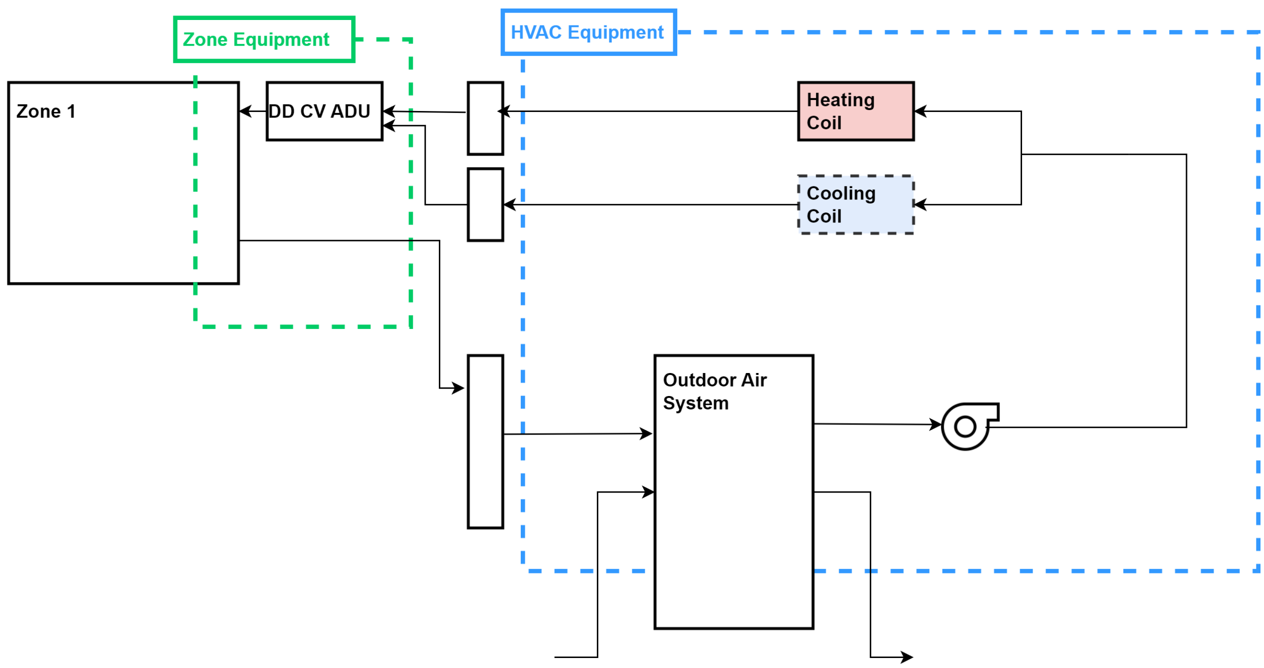


Figure 4.10 A schematic diagram of dual-duct ventilation system

4.2.3 With mechanical ventilation and cooling

Following the conclusion in section 3.4.2, DX cooling is modeled and the cooling coils are added in the central air loop of to the ventilation system with re-circulation (Variation 1) and the dual-duct system (Variation 3) from section 4.2.2as in the schematic diagrams shown.

Both models use the `Coil:Cooling:DX:TwoSpeed` object to model the operation of the DX coil. The performance characteristics of the cooling coils are the same as those used in the DOE pre-1980 Primary school model, for lack of more adapted information.

Variation 1: Ventilation with recirculation

The operation of the system remains the same as described above, only a setpoint is added for the cooling coil to condition the air for central supply.

Typically, a constant setpoint of 13°C is applied, assuming that some zones require cooling all year round. Considering the fact that the model used is small, and (almost) all zones are perimeter zones, there will be no significant cooling loads in winter. A setpoint reset is implemented based on outdoor temperature, increasing the setpoint of central air to 18°C when the outdoor temperature is below 13°C, and down to 13°C when the outdoor temperature is above 18°C, varying linearly for outdoor temperatures in-between. This avoids unnecessary cooling and consequential reheating in winter.

Variation 3: Dual-duct ventilation

The dual-duct system is implemented with a similar setpoint reset. The temperature setpoint of the cold duct is controlled the same way as for the model with recirculation. A setpoint control is added to the hot air-duct. If the outdoor temperature is below 0°C, the temperature setpoint is 43°C. If the outdoor temperature is above 21°C, the setpoint is 21°C. For temperatures in-between, the setpoint varies linearly between the two specified setpoints.

CHAPTER 5 SIMULATION RESULTS AND DISCUSSION

5.1 Weather data used

Since the models will be compared to the energy consumption data of real schools, it is important to select an appropriate weather file for simulation.

Figure 5.1 shows the locations and energy use intensity for the school buildings in Quebec[1]. While there are variations in climate and yearly weather conditions across Quebec, Figure 5.1 shows that there is no apparent trend between location and EUI. The variability of EUI amongst schools in the same location is as large as the variability seen across different locations.

Ideally, for the base model validation, the variation in climate should be taken into account, but considering that the largest number of schools are located in and around Montreal, it is assumed that this region will have the highest weight in the statistics. In a recent study [60], the authors have associated all weather stations present in the CWEC (Canadian Weather for Energy Calculation) database [61] to a population weight, by drawing Voronoi polygons around all stations and distributing the population reported in census data within those polygons. Their results show that the McTavish weather station, located in the city center of Montreal, is associated to the largest population weight (15%, with other stations in the greater Montreal region representing more than 50% of the population). We have decided to perform all simulations with weather data from the McTavish station.

The base model should be representative of the school building stock, and this is assessed by comparing its results to metered energy data, which was only available for the year 2016-2017. The weather data of the year 2016-2017 is then used for that comparison, to eliminate any effects from yearly variation in meteorological conditions. The weather data file was obtained from the SIMEB weather data service [62].

On the other hand, further discussion of the results and the comparison between model variants will use the Typical Meteorological Year file from the same weather station, using the CWEC files published by Environment Canada [61].

[1]Not all the buildings are represented because it was not possible to automatically map all the addresses in the file geospatially.

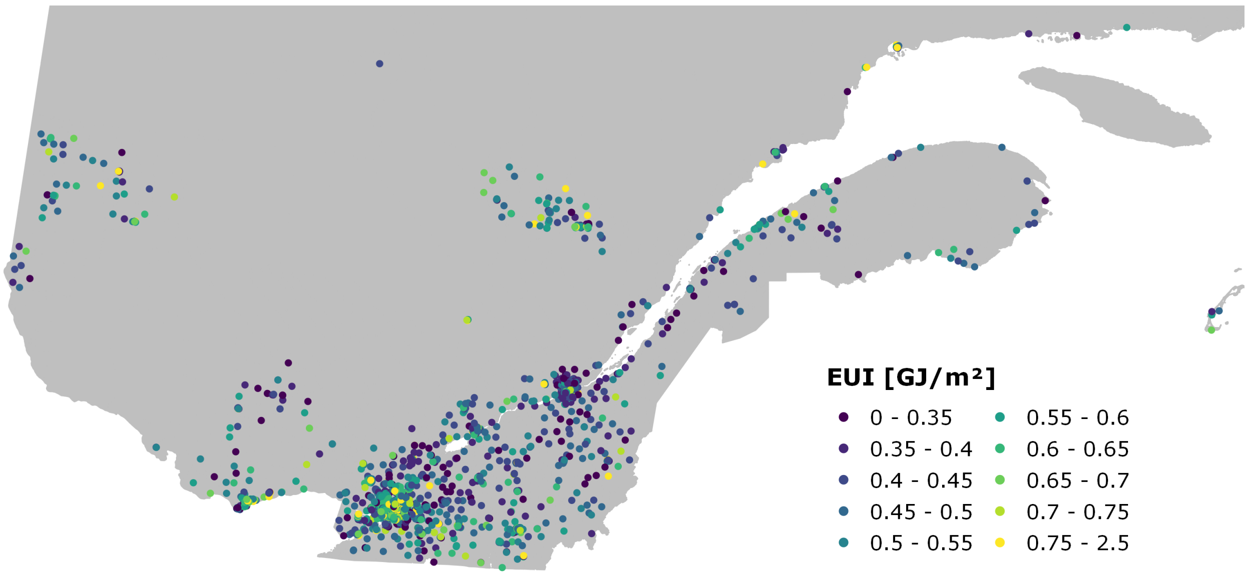


Figure 5.1 The location of schools and their Energy Use Intensity (EUI)

5.2 Assessing the representativeness of the base model

The total energy consumption of the model for the year 2016-2017 is 740.4 GJ, with the total floor area of the model being 1640 m², this comes down to an EUI = 0.45 GJ/m².

For validation, the EUI is compared to the metered energy consumption of the buildings labeled as **E0**, representing buildings which use electricity as their main energy source and which do not have any heavy-use space types. Figure 5.2 shows the spread of the energy use intensity of the **E0-Type** schools, with an average and median around 0.43 GJ/m², and 50% of the buildings having an EUI between 0.37 and 0.50 GJ/m².

As discussed in section 3.4.1, there is also metered data on peak consumption.

Figure 5.3 shows the spread of the peak electricity consumption per square meter for only those buildings which are labeled as **E0** (which additionally do not use any other energy sources). The median and mean are 0.048 kW/m² and 0.051 kW/m² respectively. This corresponds to an electricity peak of 78.7 kW and 83.6 kW respectively for the size of the building modeled.

The simulated peak electricity consumption however is 185 kW (of which 158 kW for heating). This is more than twice the average metered peak, and corresponds to a relative peak of 0.11 kW/m², which falls far outside of the range seen in the metered data, indicating a flaw in the model's ability to estimate peak demand.

A variation of the model was made in which the heating capacity was reduced by 50 percent.

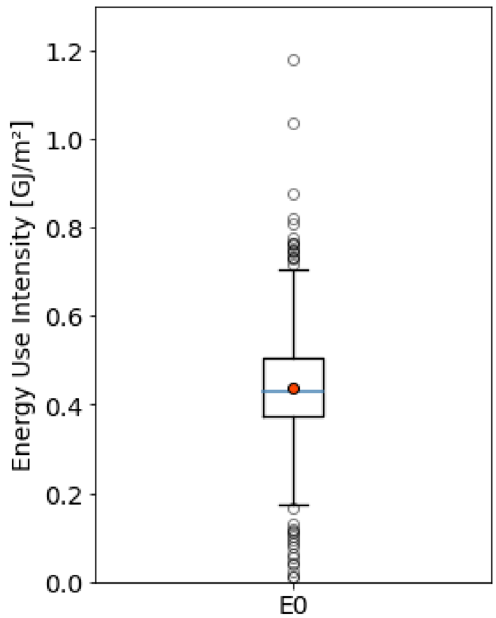


Figure 5.2 The spread of energy use intensity of **E0-Type** schools

The ability to maintain zones at heating setpoint was only minimally impacted, as is shown in figure 5.4. The largest impact is on the time it takes for the zone to reach setpoint temperature in the morning. The maximum peak was reduced to 120 kW (of which 99 kW for heating), which while still high, falls in a more reasonable range with respect to the metered electricity peak. This indicates that the automatic sizing of the equipment in the simulation may result in oversizing of the equipment to an unjustified extend, allowing unrealistic peaks to occur during simulation.

This tendency is present in all variants simulated, as peak consumption for models with mechanical ventilation and models with cooling increases to 200 kW (for all models). While the simulated peak increases only minimally with respect to the baseline model, it remains unrealistically high compared to the metered data. This is why peak demand will not be included in the further general discussion, except for the discussion of the impact of modeling choices on dynamics.

The comparison between the simulation results and the metered consumption data have been summarized in table 5.1.

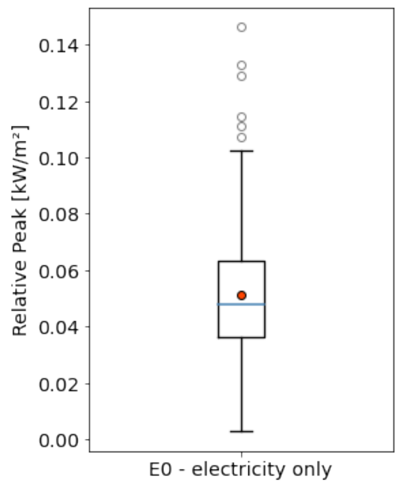


Figure 5.3 A boxplot showing the spread of the relative peak electricity consumption [kW/m²] for schools labeled as **E0** and using no other energy sources than electricity (n=325).

Table 5.1 Summary of simulation results and metered consumption data

	Building Model	Metered Consumption
EUI [GJ/m²]	0.45	0.43
Peak Electricity [kW]	185	78.7

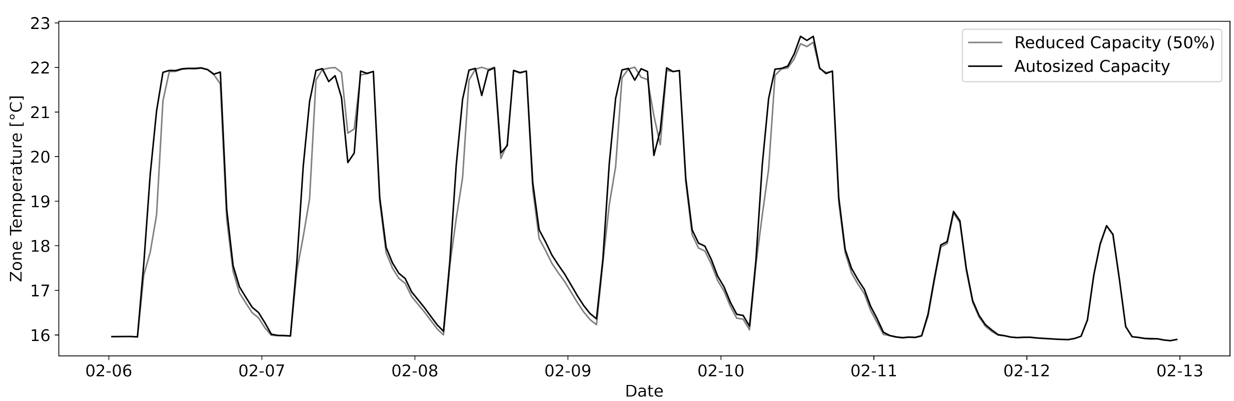


Figure 5.4 The zone temperature for simulation with an autosized capacity and simulation with a capacity reduced to 50%. The ability for the zone to maintain setpoint, despite the significantly reduced capacity, shows that autosizing could be overestimating the required installed capacity.

Figure 5.5 shows the monthly energy consumption simulated by the baseline model (using the TMY weather data). The simulation shows that during colder months, heating constitutes a very significant part of the total energy consumption (up to 75% in January). The consumption profiles of lighting, equipment and auxiliary is constant throughout the year because of the nature of these loads, except during the summer months, when the building is assumed to be out of use, the consumption drops to a minimal level.

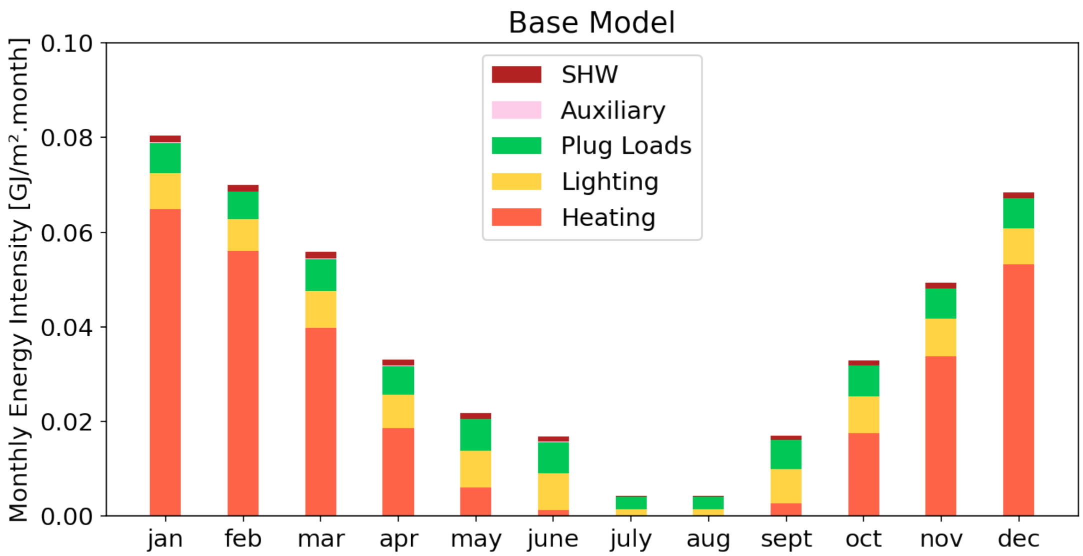


Figure 5.5 The monthly energy consumption of the baseline model, broken down by end-use

A breakdown of the yearly energy consumption is shown in fig 5.6. The shares of end-uses are compared to data in Natural Resources Canada's Comprehensive Energy Use Database [1] for the year 2019. Keeping in mind that the CEUD statistics consider all educational services, the breakdown compares well. The breakdown of end-uses is shown relative to the total consumption because the energy use intensity presented by the CEUD seems high (EUI=1.42 GJ/m^2), even when taking into consideration that cégeps and universities are also included in these statistics [2].

An estimation of the average share of heating is done using metered data. For buildings labeled as using predominantly fossil fuels, on average fossil fuels make 67% of the total energy consumption. The share of fossil fuels varies for the majority of buildings between 50 and 75%. Assuming that some of these buildings use additional electric heating [42] [43], but also keeping in mind these buildings have a proportionally higher consumption for heating because

[2]It should also be noted that the statistics presented by the CEUD have changed in recent years. Data downloaded in 2018 showed for the year 2016 an EUI = 1.14 GJ/m^2 for the educational building stock.

of the lower efficiency using fossil fuels, the average value is represented as an estimation of the consumption for heating.

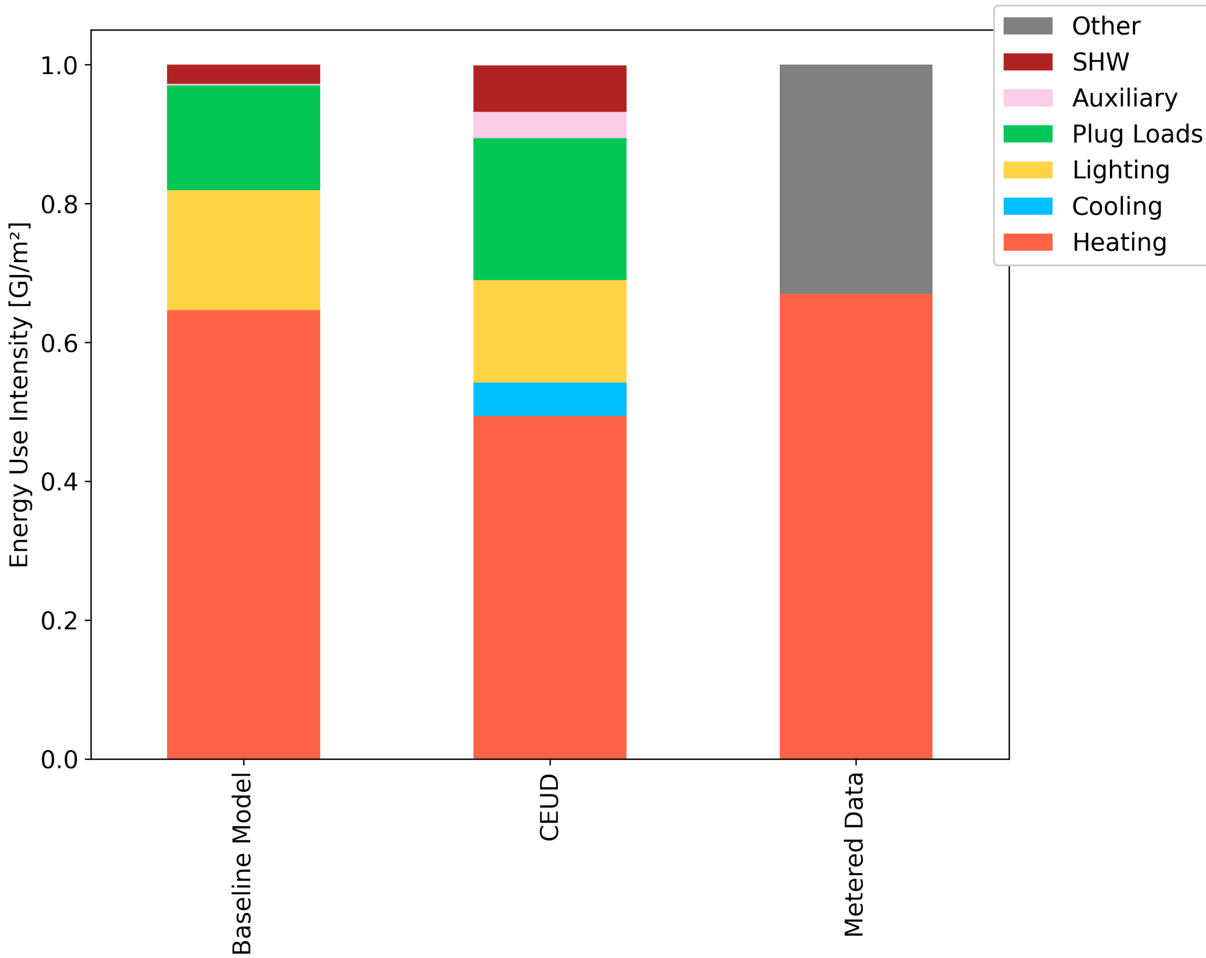


Figure 5.6 Share of energy end-uses for the baseline model, CEUD data for Quebec educational buildings, and metered energy use in Quebec schools

5.3 HVAC systems results and analysis

The results of the simulations of the HVAC system variations are discussed on different levels. First, an overview of the annual and monthly simulation results of all variations are shown and discussed on a high level. Then, a more detailed analysis will be performed by comparing certain variants to highlight some important aspects of the dynamics of the simulation and their impact on simulation result interpretation.

Figure 5.7 shows the yearly energy consumption, broken down by end-use. Models belonging to the same category are similar in energy use intensity and end-use shares, but the different HVAC categories differ significantly in EUI and end-use breakdown. This shows the large impact the HVAC categorization has on the simulated energy consumption.

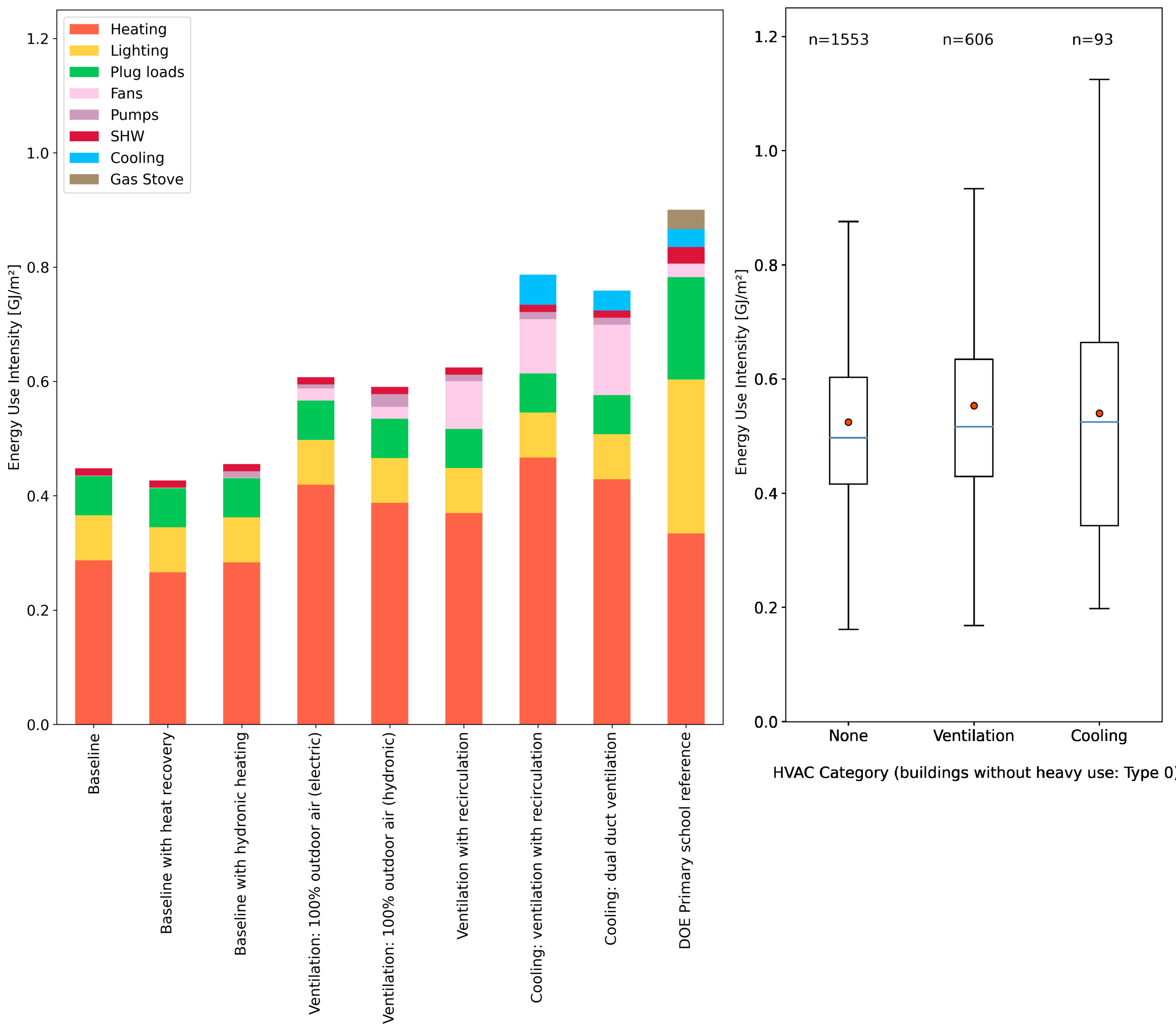


Figure 5.7 A comparison of the EUI for the baseline model, the variants of HVAC systems and the DOE Primary school reference building model and their end-use breakdowns, compared to the statistics of EUI derived from metered consumption for the different HVAC categories.

Models with mechanical ventilation show an increased heating consumption. The impact is less for ventilation with recirculation because of the larger energy consumption of the fans, reducing part of the heating load by the losses from the fan to the air stream.

Models with active cooling have an increased heating and an additional cooling load, as well as a significantly higher fan energy consumption. The model with recirculation has the highest cooling load, but also an increased heating load, because of its inherently inefficient operating principle, where air is centrally cooled and sometimes reheated for individual zone thermal control.

The stacked bar on the right shows the breakdown for the DOE Pre-1980 Primary School reference building model, showing how the model's EUI and end-use shares deviate from those of the newly developed models.

A figure showing the spread of EUI for each HVAC category of real school buildings is added on the right. The buildings shown in the spread are those without any heavy use spaces (which are categorized as **Type 0**), to eliminate the effects of the heavy use spaces on the EUI. The plot does include buildings using other energy sources than electricity to maintain a large enough representation in each category, which results in a slightly higher EUI on average because of the decreased efficiency of non-electric heating systems, as is mostly visible in the comparison of the Baseline model with the real consumption of buildings without ventilation or active cooling.

The average values of the real energy consumption fall much closer together than what is simulated by the models of respective categories, which means that the extent of the impact of simulation is not reflected by the real consumption data. There are several possible contributing factors to this. It is likely that even though a building is categorized as having a mechanical ventilation system or active cooling, this does not mean the whole building is served by the system. This would reduce the impact it has on the building's EUI. The large spread of the EUIs could reflect this, as the buildings with partial systems bring down the average, while buildings fully served by a certain system are represented by the higher ranges. Other factors play a role on the variation in EUIs as well and without having more information on individual building systems and their energy consumption this can not be confirmed with certainty, but the trends shown here and the information obtained on the few buildings' detailed system layouts suggest that this is a contributing factor.

Secondly, there is the uncertainty on characteristics of HVAC system-components and their controls, which will be discussed in detail in following sections. The systems modeled represent typical implementations and use common controls. They do not reflect any real building HVAC system or attempt to model an average (as is not really possible anyway, as will be discussed later). This means that the simulation results show what impact an HVAC type *can* have on building energy consumption, it does not represent any average or typical consumption patterns.

Figure 5.8 shows the monthly energy consumption for all variants. Again, the models belonging to the same HVAC system category show similar profiles, but are clearly distinguishable per category. The systems with active cooling behave differently form others and differently from each other: the system with recirculation shows a very particular profile, separating itself from the dual-duct system with active cooling. Further discussion follows.

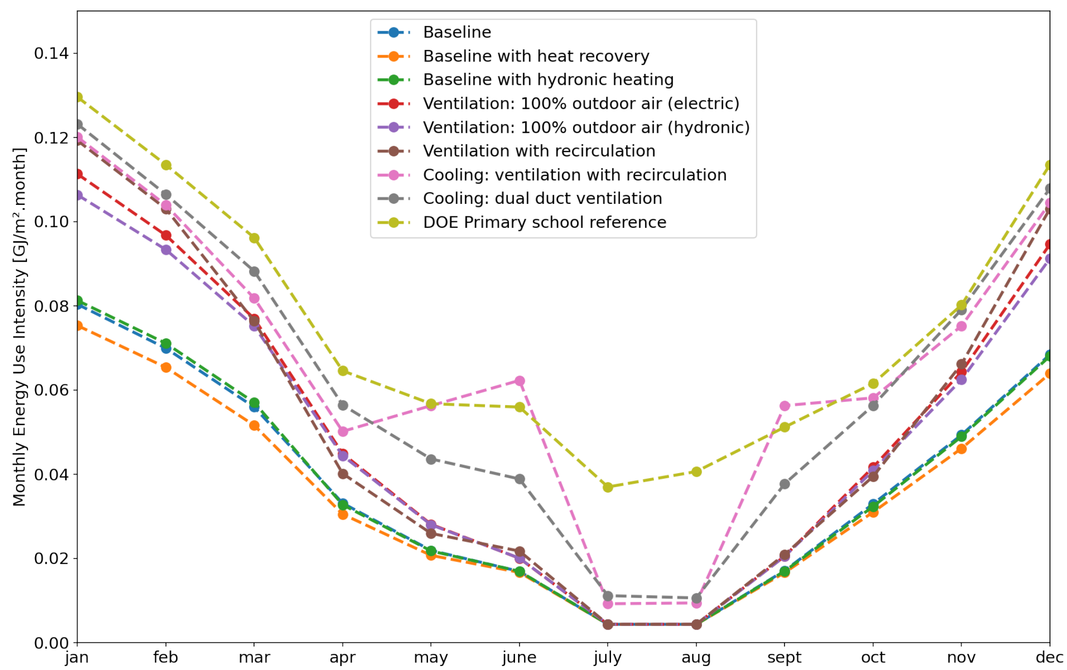


Figure 5.8 A comparison of the monthly consumption profiles for the baseline model, the variants of HVAC systems and the DOE Primary school reference building model.

5.3.1 Detailed discussion: without mechanical ventilation

In the following subsections, the two variants of the base model will be discussed and compared to the base model. As could be seen on figure 5.7, there is a relatively low impact on yearly energy consumption, but the discussion following will show the impact on dynamic profiles.

Heat recovery on exhaust VS. base model

Adding heat recovery to the exhaust air of the gymnasium and cafeteria only impacts the energy required for heating and the fan consumption. The total energy consumption is reduced by 4.7%. The peak electricity consumption is reduced by 5% while the peak electricity consumption for heating remains the same, which will be discussed below with the help of figure 5.11.

Figure 5.9 shows the total consumption and consumption for heating for several days in January. The figure illustrates how the energy consumption is reduced during the day thanks to the use of heat recovery. On most days, the peak consumption for heating is not reduced, however. This is because the highest heating load takes place before the start of the school day, as the building is heated after the night setback, while the exhaust system is only activated once the building is occupied. Figure 5.10 zooms in on two of these days to illustrate that when the peak for heating occurs after 9 a.m. (Figure 5.10b), it is reduced thanks to the heat recovery system, but otherwise a peak still occurs (Figure 5.10a).

This explains why the total electricity peak is reduced in the model, but the peak for heating is not. Figure 5.11 shows the day on which both peaks occur. The peak for heating occurs just before 9 a.m. After 9 a.m. the consumption for other end-uses (lighting, plug-loads,...) picks up because of the start of the day, while the heating loads remain constant, resulting in a total electricity peak just after 9 a.m. This peak is avoided in the ERV-model because of the reduction of the heating load.

This brings to light that while the energy savings would occur regardless of the dynamics of the building, the impact on the peak energy consumption is largely dependent on relations between the schedules defined in the model.

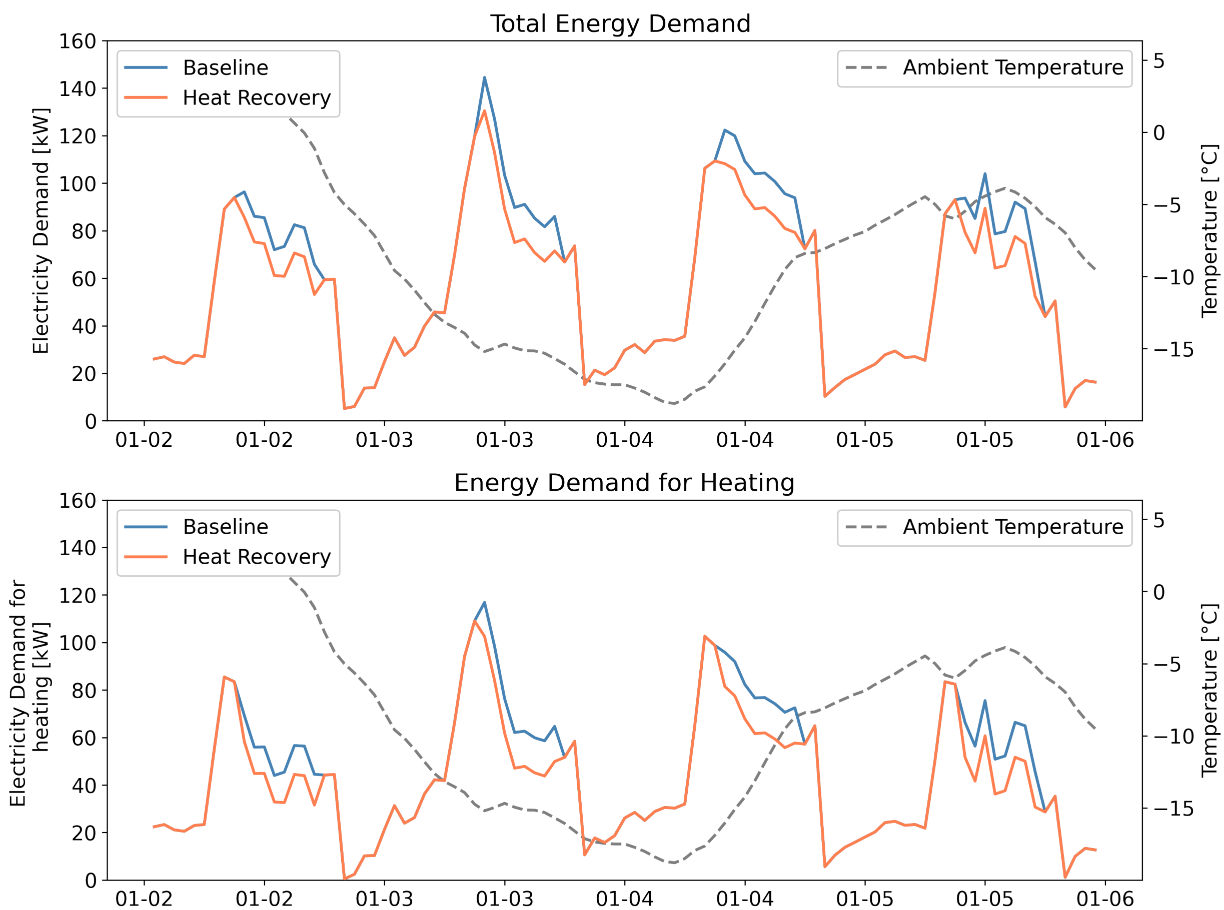
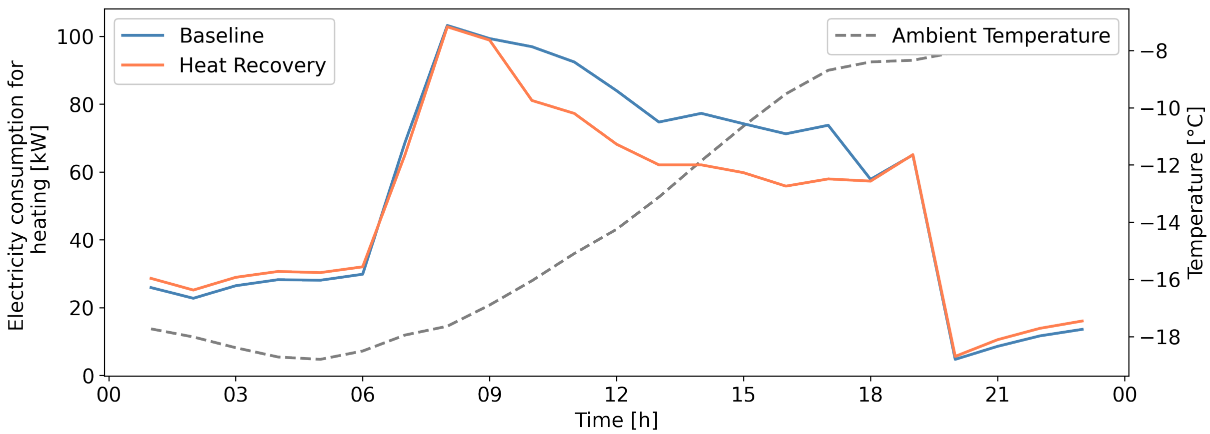
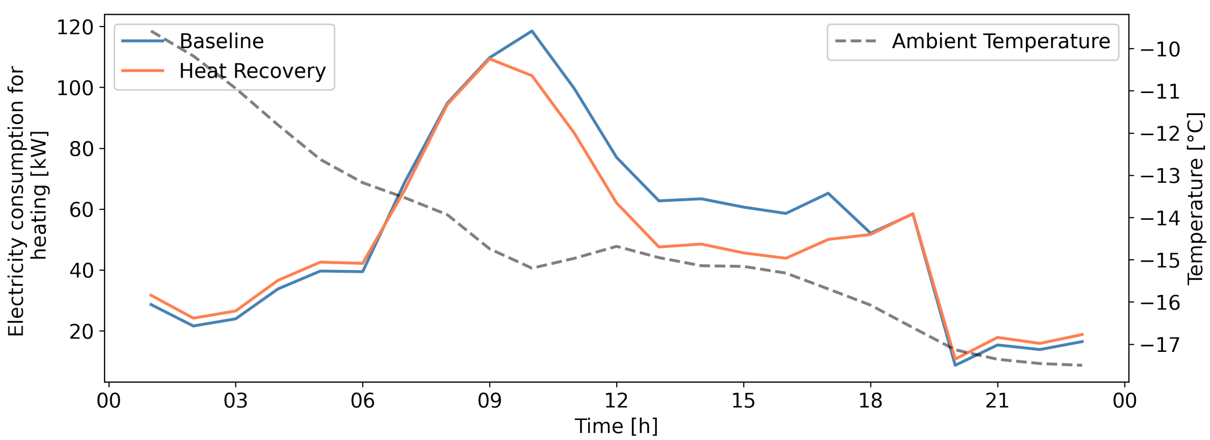


Figure 5.9 The total energy demand and heating energy demand for the baseline model and the model with heat recovery on exhaust, showing the impact of heat recovery on the dynamic profile.



(a) Jan 4th



(b) Jan 3rd

Figure 5.10 The energy demand for heating zoomed in to two different days to shows the relation of peak reduction to the schedules defined in the model. The exhaust system starts up at 9 a.am. The heat recovery system only reduces the load on days where the peak falls after the startup of the exhaust (and heat recovery).

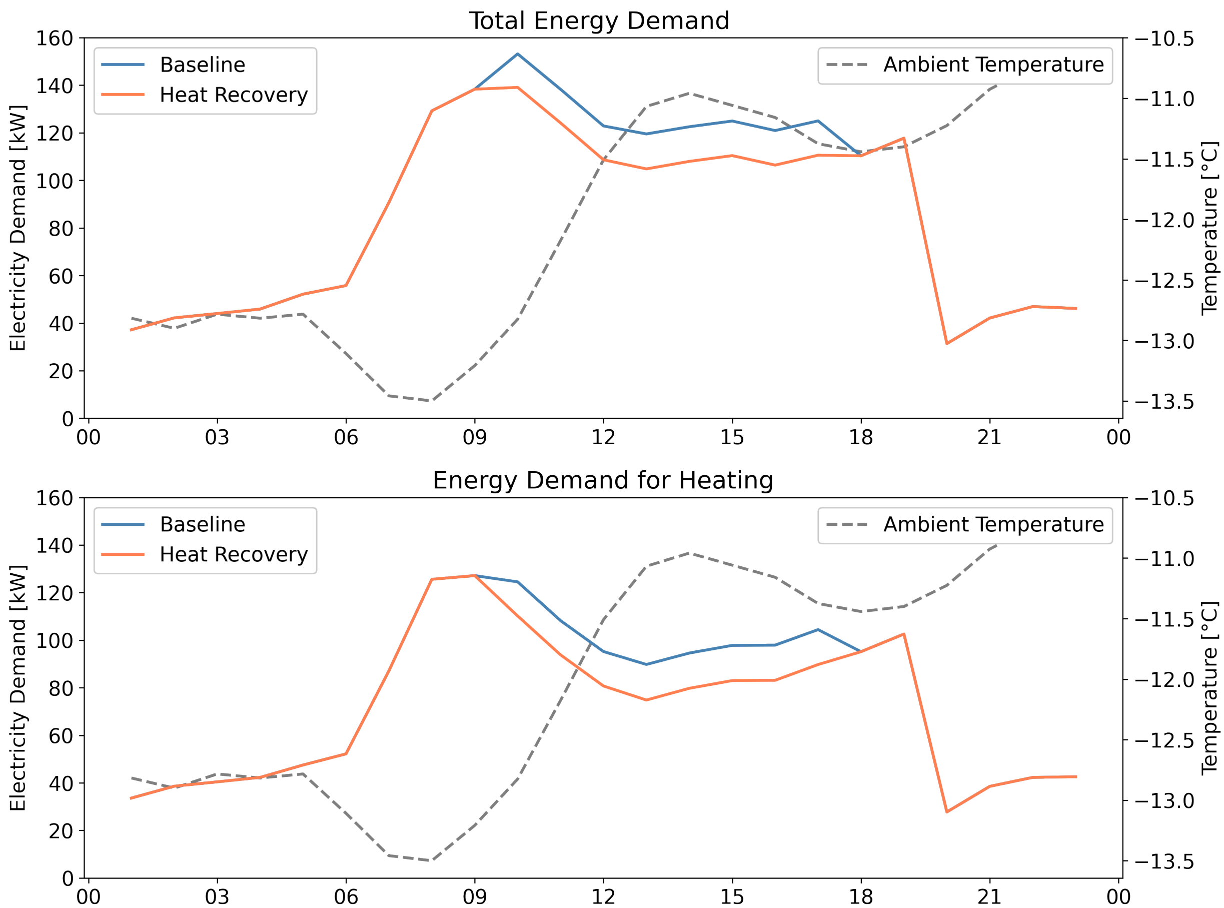


Figure 5.11 The total energy demand and heating energy demand on the day of peak consumption, illustrating how the heat recovery does not reduce the peak for heating, but does allow to reduce the total electricity peak.

Centralized hydronic heating VS. base model

Figure 5.12 shows the dynamic profile of the total energy consumption and the energy consumption for heating for a period in February. The bottom graph shows that, in the morning, the peak is reduced thanks to the inertia provided by the thermal storage of the water in the plant loop. What is remarkable, however, is the sudden peak in heating demand at arbitrary moments during the day. These peaks correspond to moments where in the hydronic model, the windows are opened in several zones at once and natural ventilation occurs, when it does not for the base model. The hydronic heating allows significantly more natural ventilation to occur. Because of the inability to coordinate the natural ventilation between the models, it is not possible to compare the simulation results in a meaningful way.

The comparison between electric baseboards and hydronic heaters will be discussed using a building model with mechanical ventilation, following in section 5.3.2.

This does bring to light an important aspect of the modeling of natural ventilation and how simulation results should be treated with this in mind.

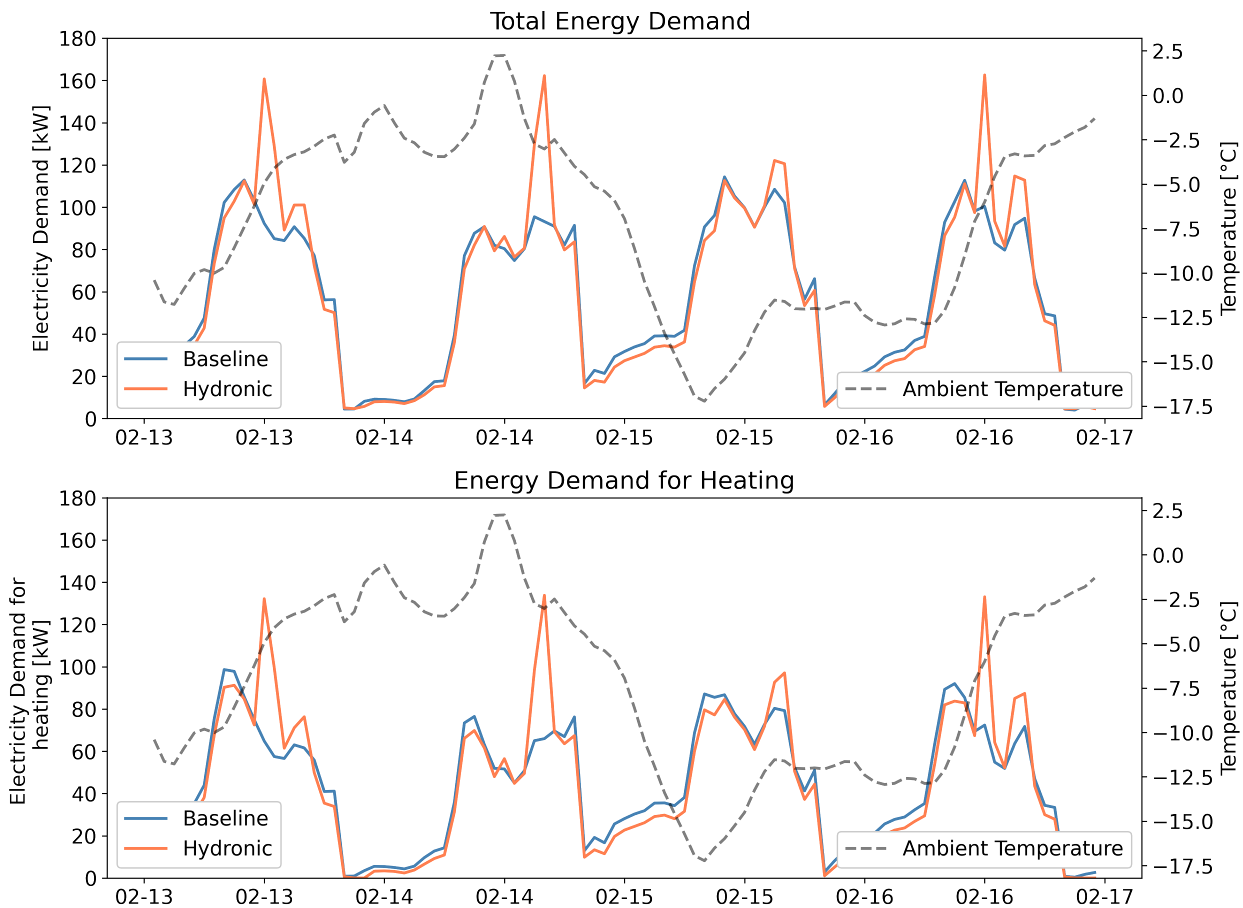


Figure 5.12 The dynamic profile of total energy demand and heating energy demand for the baseline model and the model with hydronic heating.

5.3.2 Detailed discussion: with mechanical ventilation

100% outdoor air VS. base model

Figure 5.13 shows the total energy demand and the energy demand for heating for the model ventilated with 100% outdoor air against the profile of the base model. The model with mechanical ventilation increases the heating load significantly because of the larger intake of outdoor air compared to the base model.

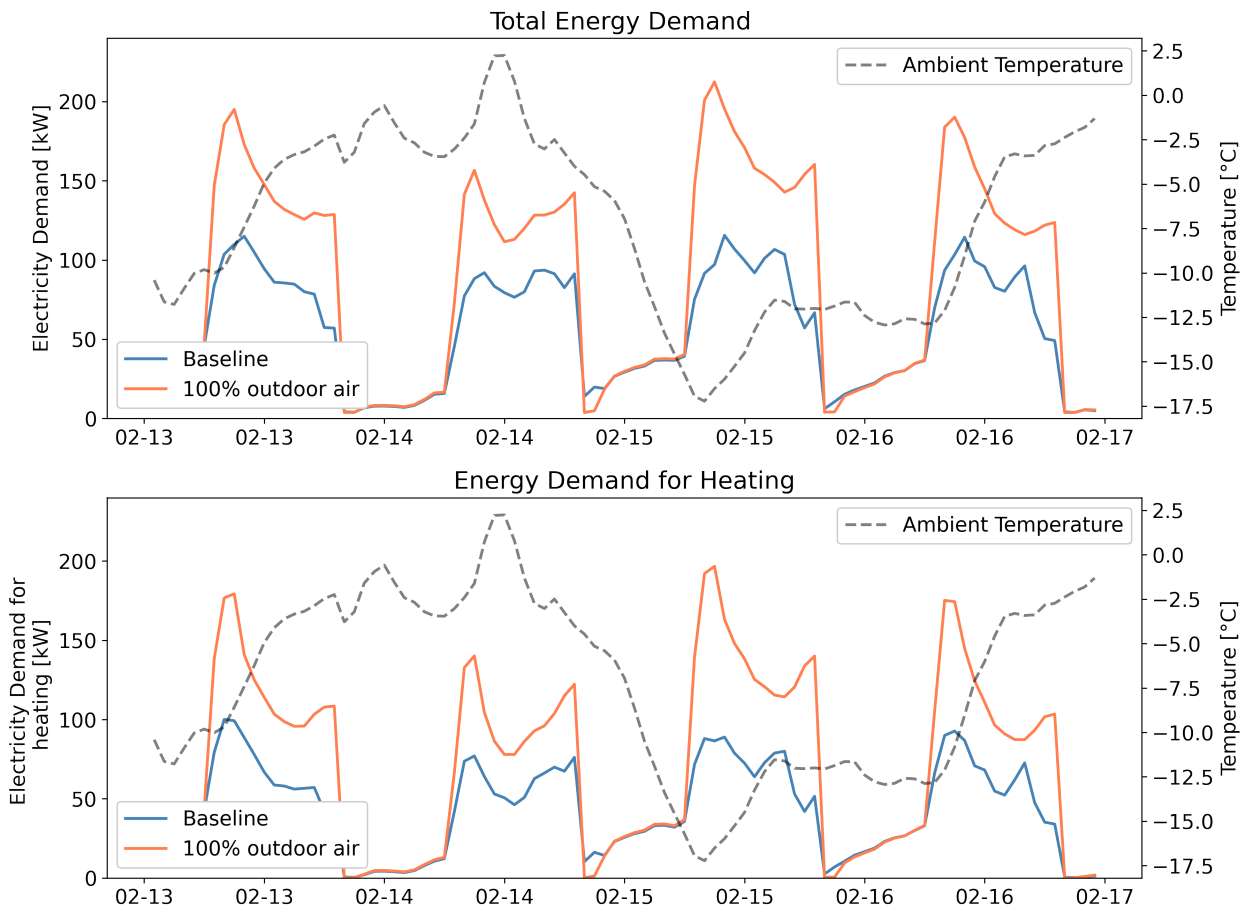


Figure 5.13 The impact of the introduction of mechanical ventilation on the dynamic profile, showed by the comparison of the energy demand and heating demand profiles of the base model and the model with mechanical ventilation with 100% outdoor air.

Centralized hydronic heating with 100% outdoor air VS. 100% outdoor air

Because the hydronic heating has an impact on the level of natural ventilation, the system is instead compared for a model with mechanical ventilation to maintain similar conditions. Figure 5.14 shows the demand profiles for the 100% outdoor air model with electric or hydronic baseboard heaters. The heating demand shows how the hydronic system has a slightly reduced demand during the morning warm-up of the building thanks to its thermal inertia, as mentioned before. It is however not enough to actually reduce the peak demand.

The figure also illustrates how, during the night, the hydronic system consumes consistently less than model with electric baseboards. Looking into this has brought to light what seems to be an inconsistency in the modeling of the electric baseboards. Where the part of the energy that is emitted into the zone by radiation should be absorbed by the surfaces in the zone and contribute to delayed convective gains, this appears not to be the case according to more detailed output reports.

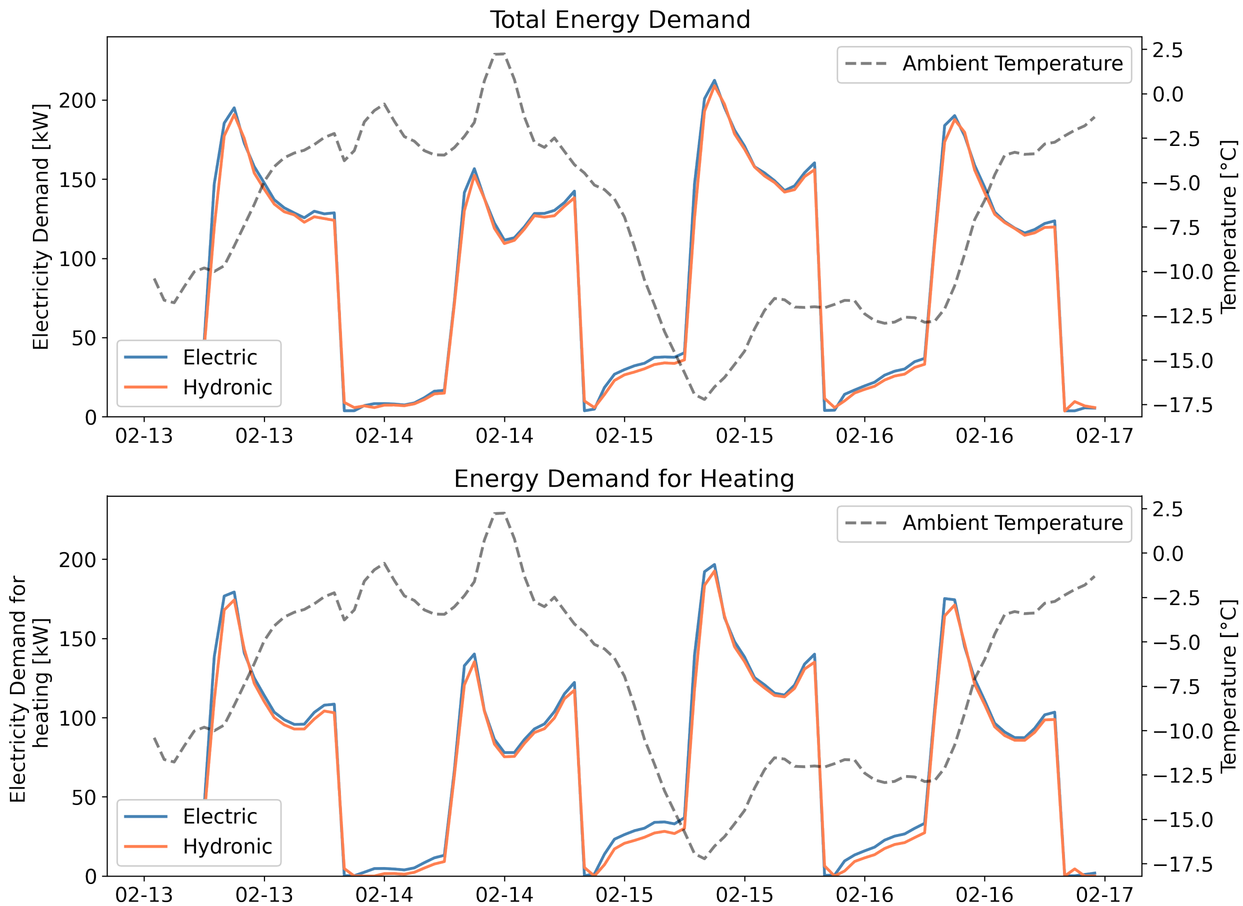


Figure 5.14 The comparison of dynamic profiles for electric baseboards and hydronic heating for the model with mechanical ventilation with 100% outdoor air.

Figure 5.15 shows the reported variables related to a baseboard in an arbitrary zone for both the electric and the hydronic model. The baseboard *convective* and *radiant heating rate* represent the heat transferred from the baseboard into the zone. The *total heating rate* is documented as the "actual convective heat addition rate of the baseboard to the zone in Watts. This value includes the heat convected to the zone air from the baseboard unit, the heat radiated to people in the zone from the baseboard unit, and the additional convection from surfaces within the zone that have been heated by radiation from the baseboard unit." [63]. Given that the radiant heat of the baseboard transfers energy to the surfaces in the zones, this energy will be then transferred to the zone's air by convection, resulting in a *Total heating rate* which is higher than the *Baseboard convective heating rate*. These reported variables for the hydronic baseboard are consistent with this documentation, but the variables reported for the electric baseboard are not.

While it is unclear how the radiant energy is accounted for, the energy does not seem to be lost however, as modeling the baseboards with a radiant fraction of zero (instead of 0.2) only reduces the energy consumption for heating by 1.5%. This does result in different behaviors between the hydronic and electric baseboards in the simulation.

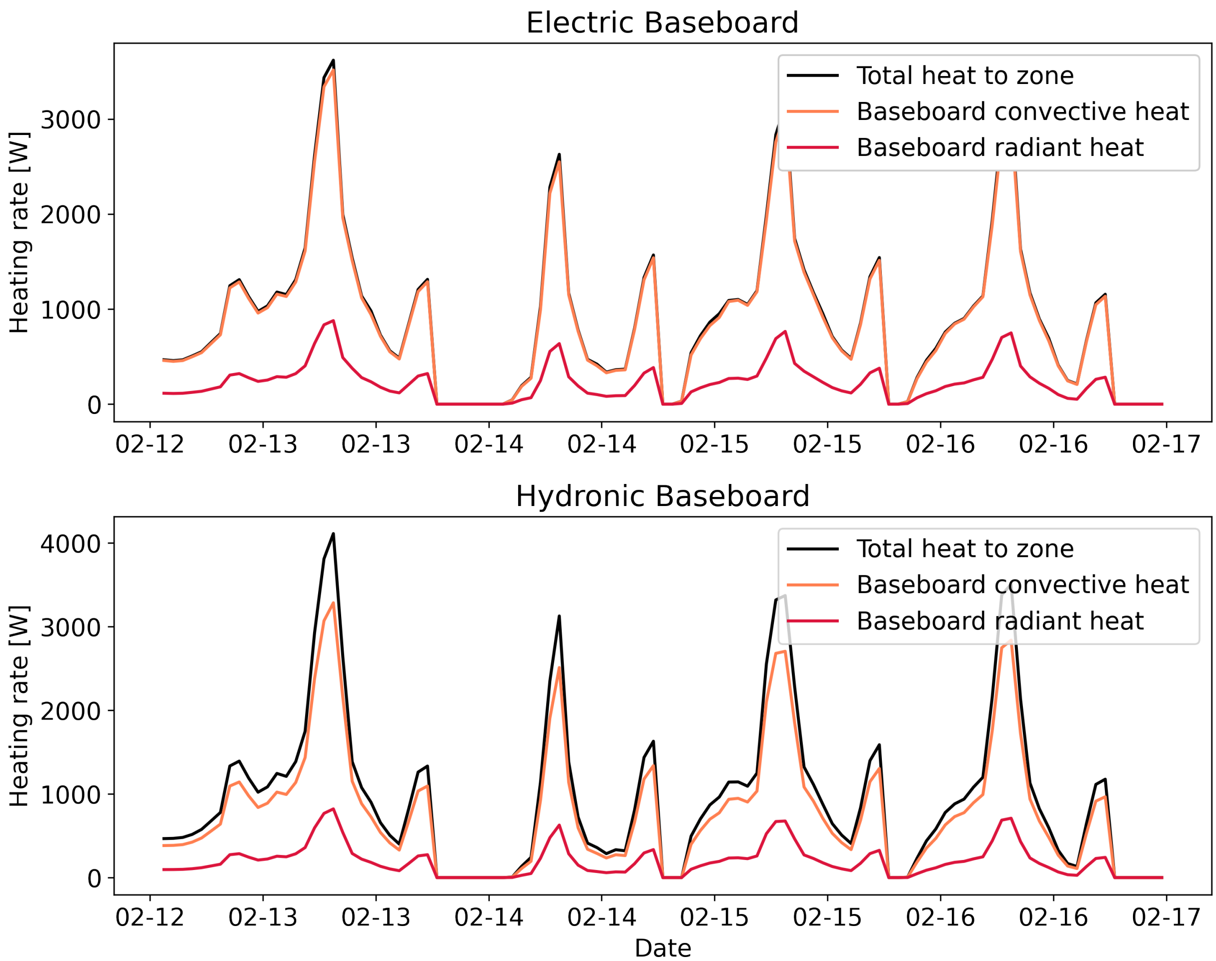


Figure 5.15 Reported variables related to the heat transfer from electric and hydronic baseboards, showing an inconsistency in the reported heat added to the zones for the electric baseboard.

Ventilation with recirculation VS. 100% outdoor air

Figure 5.16 shows the dynamic profiles of ventilation with recirculation compared to the model with 100% outdoor air. The main driver for the difference between the demand profiles of these two models is the provision of outdoor air. As explained in chapter 4, the requirements of outdoor air are defined both through floor area and through occupancy. Both models assume a constant flow-rate fan, imposing a fixed volume of air to be circulated. The 100% outdoor air model fixes the outdoor air flow rate to be at its maximum value when the system is in operation. It operates only during the day, since at night no ventilation is required and zones are kept at their setpoint temperature with the baseboard heaters. The ventilation with recirculation, on the other hand, relies on ventilation to keep zones at their temperature setpoint and uses a night-cycle to start up the ventilation whenever there is a heating demand. The system uses demand-controlled ventilation to vary the outdoor air fraction and reduce the intake of outdoor air outside of occupancy hours. This means that the ventilation system with recirculation supplies less outdoor air in average, but more continuously.

This difference in dynamics is clearly visible in the heating profiles. As the 100% outdoor air system experiences a steep peak in the morning, the system with recirculation has a softer peak as the building requires less outdoor air during start-up because of low occupancy. At night however, heating demand is higher, because there remains an intake of outdoor air.

Figure 5.17 shows the monthly energy use for the models with mechanical ventilation, as well as the baseline model. The profile for the models with ventilation fall reasonably close and are mostly distinguished from the baseline by the vertical stretch with caused by the increased heating demand due to the intake of outdoor air.

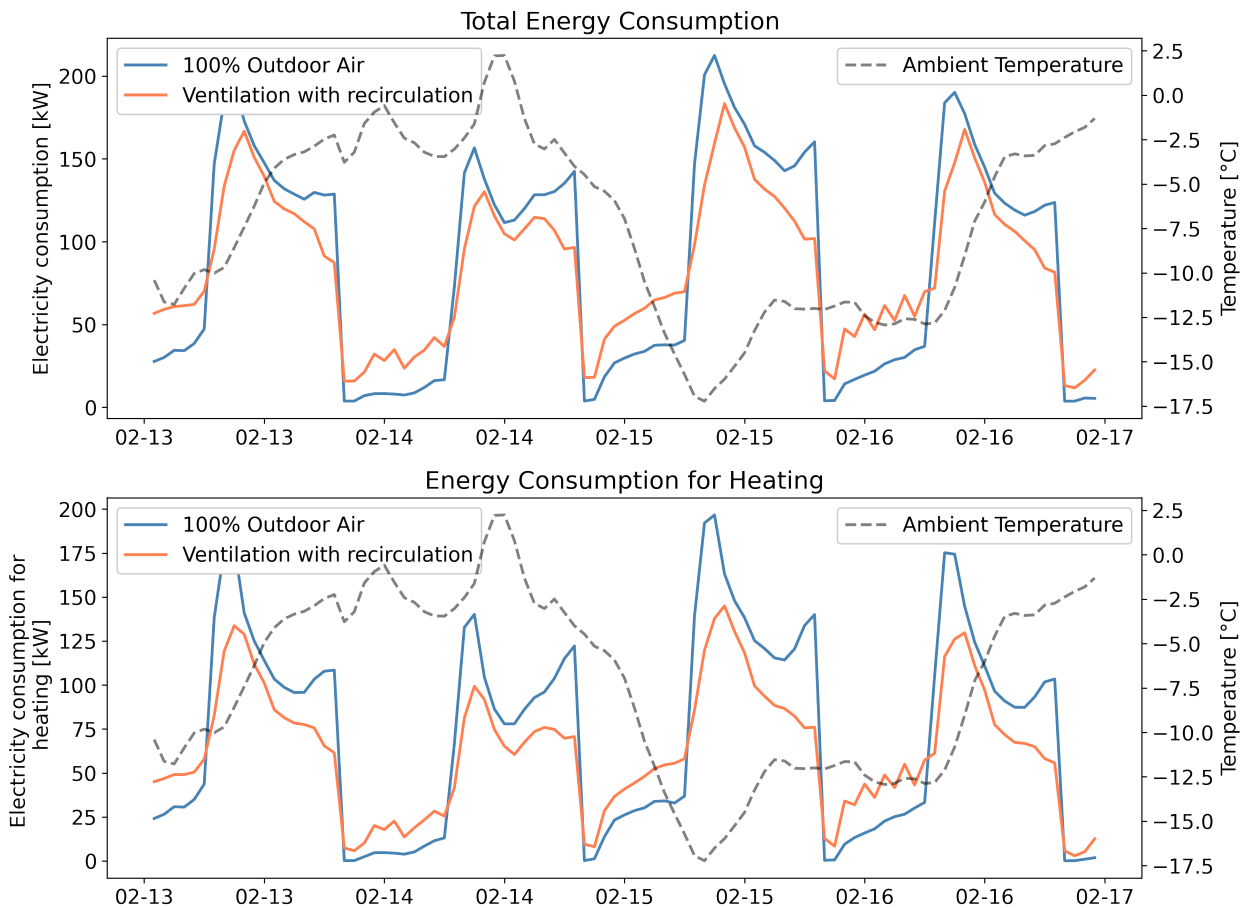


Figure 5.16 The comparison of the dynamic profiles for two models with mechanical ventilation: ventilation with 100% outdoor air and ventilation with recirculation.

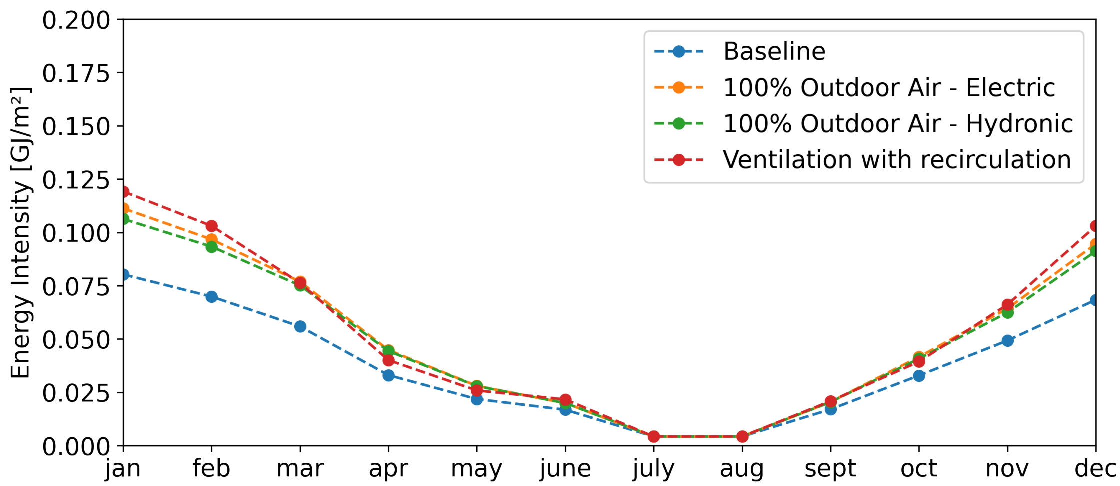


Figure 5.17 The monthly consumption profile for models with mechanical ventilation compared to the base model.

5.3.3 Detailed discussion: ventilation with active cooling

Figure 5.18 shows the energy demand for heating and cooling on a summer day for both the single duct ventilation with recirculation and the dual duct systems. The occurrence of simultaneous cooling and heating loads in the single duct system highlights the difference between the operation of the two systems. As the single duct system supplies a constant volume of air to all zones, which is cooled to the same setpoint before arriving at a zone's terminal, the reheat coil is responsible for conditioning the air to meet zone demand.

The setpoint temperature reset allows avoiding unnecessary cooling and reheating in winter, but as the simulation shows, during summer months, the central cooling setpoint still induces a considerable heating demand. The impact on energy consumption is especially visible in the monthly profile. Figure 5.19 shows the energy consumption for cooling and heating separately for the two models. In winter, there is no cooling load thanks to the setpoint reset. during milder months the system resumes normal operation, where all central air is cooled to 13°C. Because not all zones need the same level of cooling, this causes significant demand from reheating. While this co-occurance of cooling and heating loads is inherent to the single duct system, the extend of the amplified cooling and heating loads depends heavily on the selected control parameters and on the differences between zones served by the system. It is likely that some buildings operate similarly to this model, but it is also likely that systems in some buildings would be better designed and controlled to reduce or remove this heating demand during warmer months. We make no claim that these results represent the majority of operating schools, but the results highlight the significance of design and control assumptions when implementing prototype models.

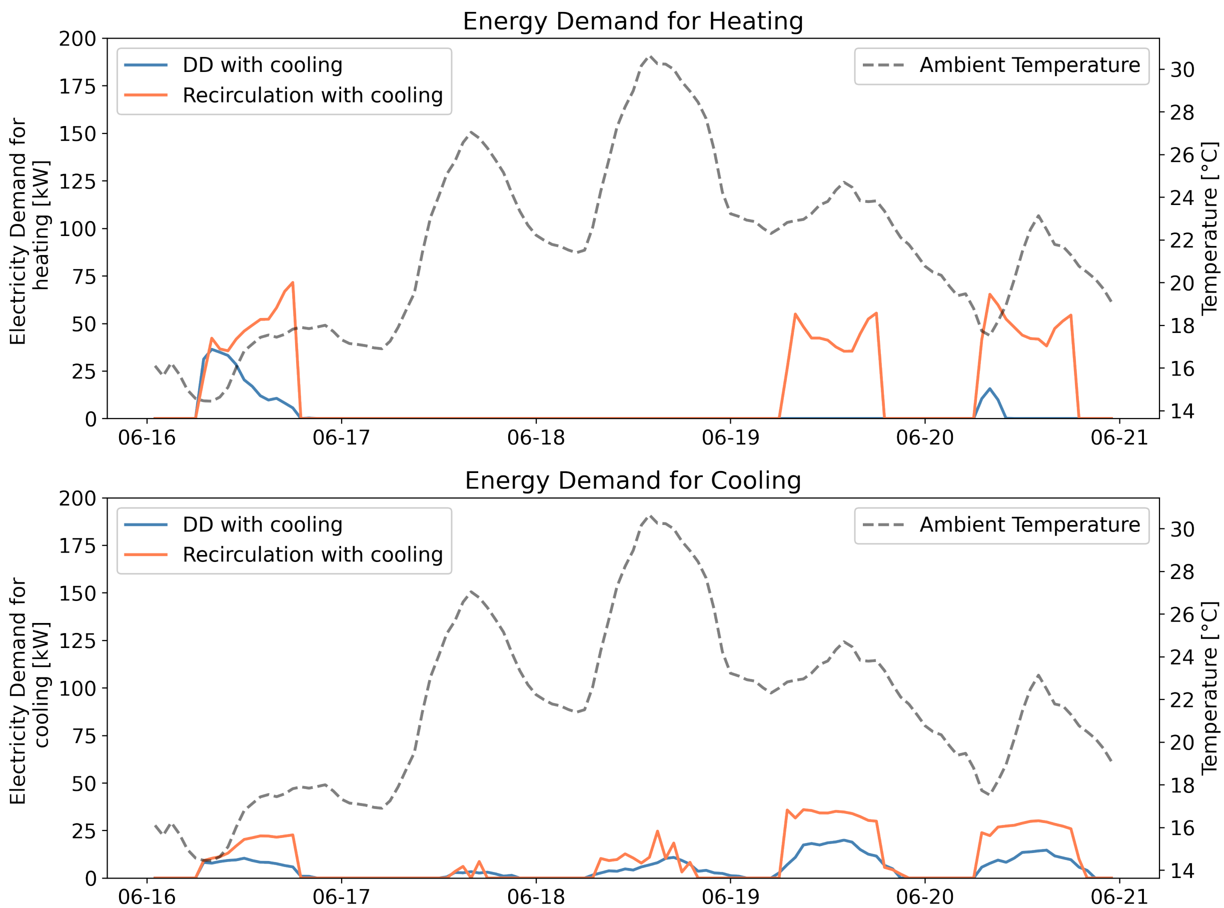


Figure 5.18 The comparison of the dynamic profiles of the two models with active cooling: single duct with recirculation and dual-duct ventilation.

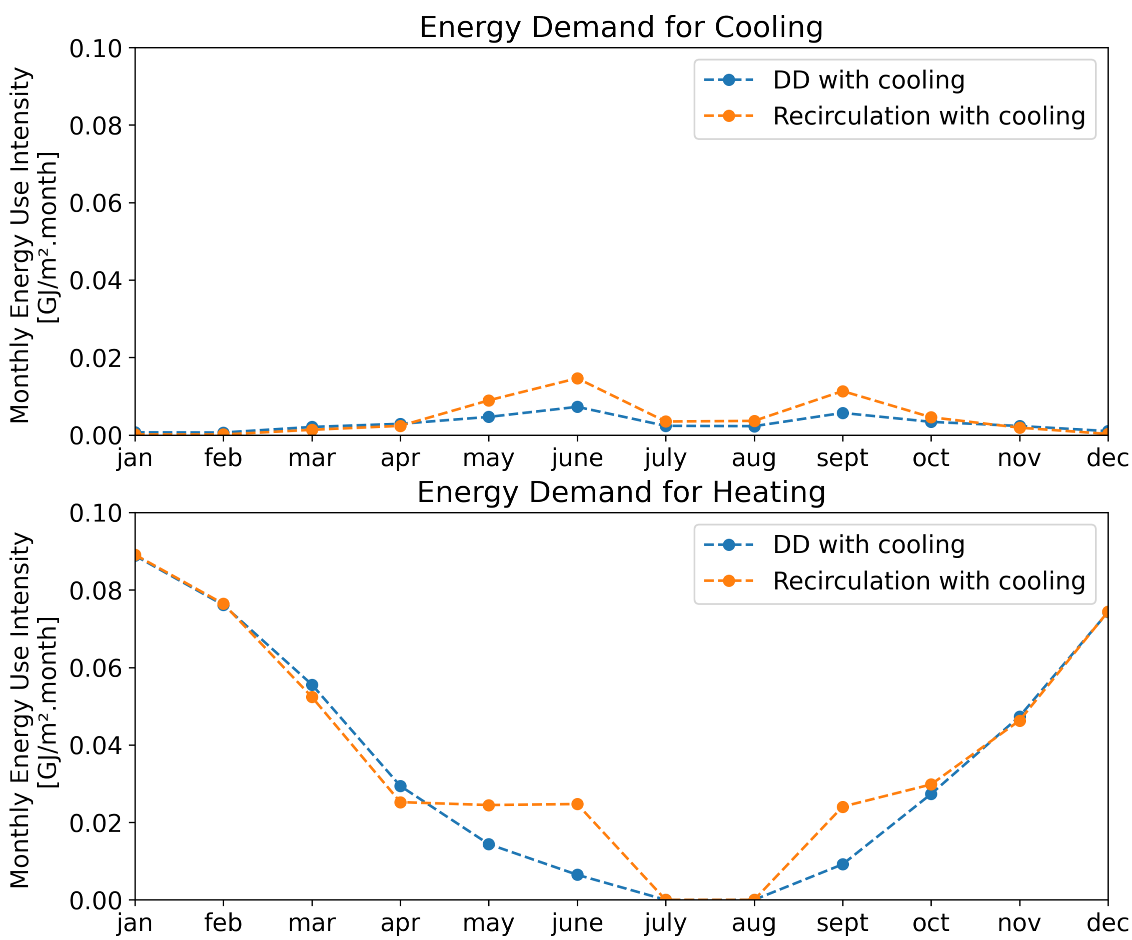


Figure 5.19 The monthly profiles of energy demand for cooling and heating respectively, for the two models with active cooling.

5.3.4 Detailed discussion: using different energy sources

To illustrate the impact of heating equipment using different energy sources, the ventilation with recirculation model is modified to simulate the use of a natural gas boiler. The modeling of a natural gas boiler is possible using either a constant nominal efficiency, or by supplying a performance curve to adapt the operating efficiency depending on part load ratio and water temperature.

Figure 5.20 shows the profile for the model with an electric boiler (with a 100% efficiency), a gas boiler with constant efficiency (80%), and boiler with an efficiency performance curve. the performance curve is the default one in EnergyPlus for non-condensing gas boilers; it has a rated efficiency of 80% with performance degradation at part-load and for higher water temperatures. The energy use of the gas boilers is higher than that of the electric boiler, as expected given the lower nominal efficiency. The simulation results with a constant-efficiency boiler can simply be obtained by dividing the results obtained with the electric boiler by the rated efficiency. In this case, the impact of using different fuels can easily be derived after simulation, not requiring a separate model. The impact of the performance curve is clearly visible on the figure, increasing the energy use at lower loads, typically during the afternoon and at night.

Figure 5.21 shows the monthly energy use for the 3 boiler variants, as well as the electric boiler results shifted by a constant ratio equal to the average efficiency of both gas boiler variants. The average efficiency of the gas boiler with the performance curve is 74%, and the graph shows that shifting the electric boiler results to match that average efficiency results in an almost perfect match on a monthly scale. The differences, however, are more significant on an hourly or shorter time steps, as discussed above.

The selection of performance parameters (rated efficiencies) and performance curve is not intended to represent a particular or "average" Quebec school, the comparison is used to illustrate the impact of considering different HVAC systems and energy sources on simulation results.

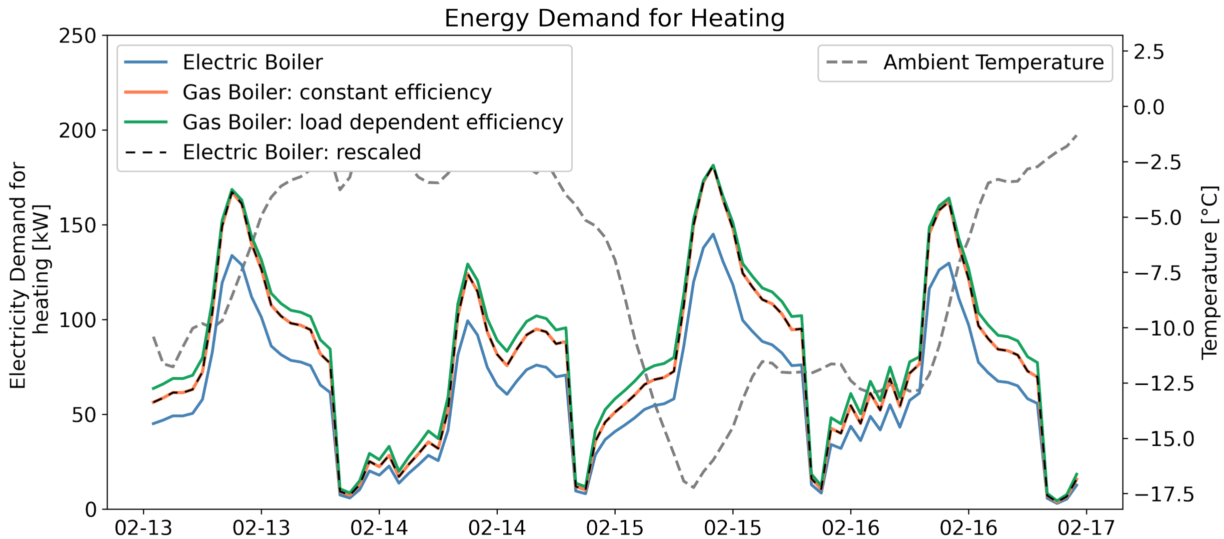


Figure 5.20 The comparison of the dynamic profile for model with ventilation with recirculation, for different boiler types, showing the impact of introducing load dependent boiler efficiency.

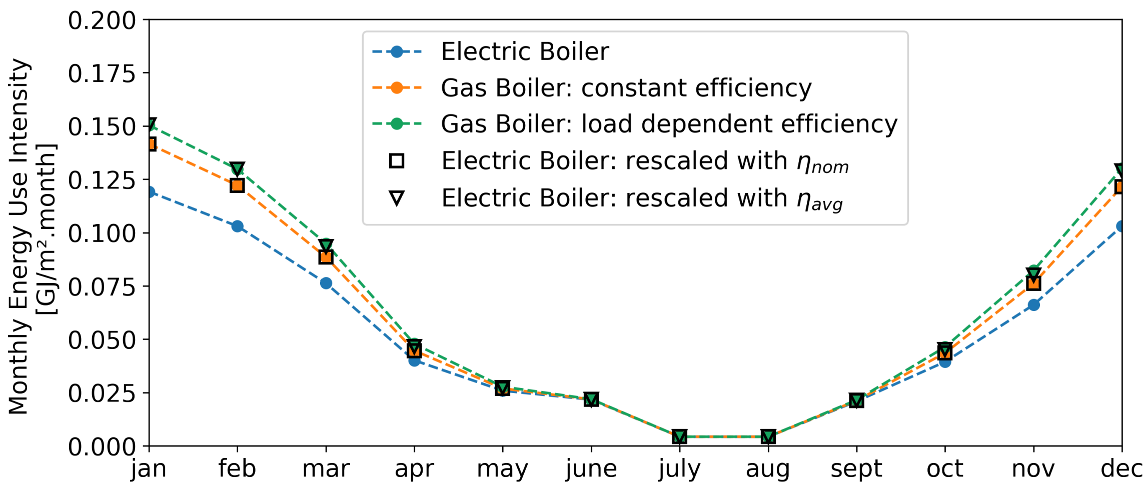


Figure 5.21 The comparison of the monthly profile for model with ventilation with recirculation, for different boiler types, showing how profiles for boilers with different operational efficiency definitions can be approximated from simulation results with an electric boiler.

5.3.5 Conclusions

The results presented in this chapter cover different possible HVAC system configurations. The results show that significant differences in consumption patterns occur between HVAC system categories because of the way the HVAC system impacts the loads of the building. The energy use intensity of the building changes, the breakdown of end-uses changes and the dynamics of the consumption change, impacting the level of peak (electricity) consumption and possibly the time of day of the peak. Within broad categories (e.g. without or with mechanical ventilation), differences can be relatively small on a monthly or yearly basis, but the differences in dynamic profiles between the sub-variants can be significant. The comparison between the 100% outdoor air system and the ventilation system with recirculation showed significant differences in daily profiles, with relatively small monthly differences. On the other hand, large monthly differences were observed between single- and dual-duct systems with cooling.

The analysis showed how sensitive the dynamic profiles are to the schedules and controls defined for a system. While there is little information on this on a larger scale, it is important to keep this in mind when using these types of models.

A correct estimation of the break-down of the end-uses of energy is essential if we want to analyse the impact of more efficient heating systems, such as heat pumps. The estimated reductions depend on a correct estimation of the contribution of a component's energy consumption with respect to the building's total energy use. If for example a certain number of electric boilers were to be replaced by efficient heat pumps, but the contribution of heating for those buildings is overestimated, this would overestimate the reduction in energy use.

The impact on peak energy consumption is important to assess decarbonization strategies based on electrification of heating. A correct estimation of impact on electricity peaks could make or break the implementation of certain technologies. EnergyPlus can simulate the dynamic profiles of energy consumption and studies have successfully modeled HVAC systems in EnergyPlus and validated the dynamics of energy consumption simulated [64] and [65]. This study, however, has brought to light an important issue in the estimation of peak demand when autosizing equipment in EnergyPlus and when relying on default control strategies.

CHAPTER 6 CONCLUSION

Prototype building energy models are useful to investigate the impact of different measures on energy use and greenhouse gas (GHG) emissions of building portfolios. This thesis addressed the development of a prototype building model for Quebec primary schools, with the aim of supporting governments efforts to decarbonize these buildings and improve their energy efficiency. When characterizing the considered building stock, a particular emphasis was placed on implementing different heating, ventilation, and air-conditioning (HVAC) systems. Different HVAC systems have been shown in the literature to deliver different levels of energy use and GHG emissions, but this aspect is nevertheless often ignored or overly simplified in developing prototype models, due to the lack of information and to the multiple configurations that need to be configured.

Rather than aiming to deliver a universal prototype model, or a universally applicable series of prototype models for Quebec schools, this work aimed to propose a general base model representing typical architectural and thermal characteristics, and to assess the impact of combining this "building shell" with different HVAC systems.

6.1 Thesis contributions

The first part of this thesis investigated the characterization of the Quebec school building stock. Compared to previous studies presented in the literature, a particular attention was paid to HVAC systems. Given the focus on HVAC systems, the analysis was used to define common characteristics for geometrical parameters. the most frequent types of HVAC systems were identified and the analysis showed that considering these different types of system was necessary to represent the energy use, peak demand, and the breakdown between energy sources, which cannot be represented adequately by an "average" building.

This characterization allowed to develop a prototype model, which represents a rectangular 2-storey primary school with a total floor area of 1640 m^2 including a gym. Construction details were selected to represent the existing building stock with an average performance level. Care was taken to include a realistic window-to-wall ratio with operable windows for variants relying on natural ventilation. The base model has no mechanical ventilation system and relies on electric baseboards for heating, representing an extremely simple HVAC system to act as a comparison point for other HVAC system types. Natural ventilation is modeled to represent the behaviour of occupants favoring air quality over energy efficiency, according to information found in the literature, which was also used to develop the daylighting controls strategy. The base configuration includes an extractor in the gym, and a first system variant implements heat recovery on that exhaust air. Hydronic heating (electrically heated or using gas boilers) is then added as an option. A broad category of mechanically ventilated buildings is then considered, with single- and dual-duct variants, and 100% outdoor air vs. recirculation. The presence of cooling is also considered.

The results of 9 HVAC systems configurations have been analyzed. The detailed results show that design and control parameters have a significant impact on dynamic profiles and monthly (or yearly) energy use, highlighting the necessity to carefully consider these aspects when developing prototype models, instead of relying on default configurations. The results detailed in chapter 5 provide evidence that the conclusions obtained from the proposed prototype model regarding decarbonization scenarios, such as switching from gas boilers to electric boilers, would be largely influenced by the variants used (or ignored) in assessing these scenarios. Similarly, assessing high-efficiency solutions such as heat pumps and investigating the impact on energy use and peak demand would require selecting the appropriate configuration—or configurations—to obtain representative results. Overall, the yearly energy use between the different configuration varies up to 53%.

This thesis has also shown that, in order to model decarbonization scenarios accurately, attention must be paid to *what* to model (system configurations and strategies), *how* to model it (choosing model "objects" in EnergyPlus, configuring them, selecting control strategies). System sizing is mostly absent from discussions on prototype and archetype models development, and while no general solution has been found, this thesis is providing evidence that the auto-sizing procedures in EnergyPlus are not adapted to Quebec schools—and probably not to other commercial and institutional buildings in the Quebec context.

6.2 Limitations and future research

The base model created is one that hosts the most common characteristics of a Quebec school building, but other typical characteristics exist. For studies using archetypical models of schools, the archetype set should be extended to represent the most important variations.

The sources used for the creation of the base model and identifying the HVAC-configurations have only been used on an aggregated level, where conclusions have been taken on each building characteristic mostly independently. But considering the sizes of each study and the extensiveness of the surveys, a more thorough representation of a typical school could be obtained using the survey data directly, as it would allow linking different characteristics together and get more insight on co-occurrences of characteristics.

An important issue with the estimation of peak demand when auto-sizing equipment has been brought to light. Prototype models have to be flexible enough to allow simulation in different conditions and easy modification of parameters without having to reconfigure the whole HVAC system manually, which makes the auto-sizing of systems a key aspect of a prototype model. This issue should be studied further in order to improve the ability for prototype models to accurately represent dynamics in demand.

The improvement of estimating the variety seen in the building stock EUI has not been studied here. Future work could estimate the school stock energy consumption by attributing the variations of models, and other variations that impact the EUI (such as the presence of certain space types, as discussed before) to the number of building types seen in the stock, to see if the distribution of EUI approaches this of the stock.

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