Retrofit of bungalow houses in Quebec to improve energy efficiency and thermal comfort

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ABSTRACT: This paper presents the results of the first phase of a Master's thesis that has for main objective to assess the energy efficiency and thermal comfort improvement potential of different retrofit strategies for the first generation of bungalow houses located in Quebec City, Quebec, Canada. The study is carried out by using dynamic energy simulations with the program Derob-LTH. In the first phase of this study, the impact of different parameters (orientation, temperature set points and natural ventilation) is analysed. The results show that the base case model of the bungalow has an energy intensity slightly below validation data according to a 1003 bungalows database. The bungalow does not have a high performance in terms of thermal comfort: overheating and a winter (cold) discomfort phenomenon are observed. The results show that south orientation is preferable but has a negligible impact; temperature set points have, contrarily, a major impact on heating demand and on thermal comfort. Finally, the results concerning natural ventilation are counter intuitive as they suggest that all day (24h) ventilation is more efficient than night-time ventilation.
Keywords: energy-efficiency, energy-intensity, comfort, thermal comfort, heating, retrofit, residential, simulation.

INTRODUCTION

In Canada, buildings account for 29% of the total energy used [2]. Around 16% of the total energy is consumed by the residential sector alone [2]. Since the building stock is being renewed at a slow rate (around 2% per year), it is essential to promote energy-efficiency improvements of existing buildings. A reduction of the overall energy consumption of buildings is not achievable without a massive retrofit of the existing housing stock [1].

Bungalow houses are the most widely spread single-family detached house type in the province of Quebec [9, 10]. The first houses, which were built between 1950 and 1970 in the earliest suburbs, represent the first generation of bungalows. These houses are located directly around the central city district. At the moment, they are being more or less abandoned due to their poor quality: young families prefer to buy newer cottage style houses in recent suburbs, on the outskirts of the city. This leads to increased commuting distances and thus more GHG emissions. The first generation of bungalow houses, which are very common, have a large potential for improvements in energy efficiency: they are poorly insulated and have high air change rates. Their energy intensity is very high compared with today's standards (Novoclimat in Quebec, R-2000 in Canada, Passivhaus in Europe, Minergie in Switzerland, etc.). Moreover, their design and orientation does not respond to local climate.

This paper presents the results of the first phase of a Master's thesis about the potential for improvement in energy efficiency and thermal comfort of the first generation of bungalow houses located in Quebec City, Quebec, Canada. The main objective of this study is to assess the energy efficiency improvement potential of different retrofit strategies and their effect on thermal comfort. In continuity, a second objective is to compare the effects of simple building envelope retrofit strategies with strategies involving architectural transformations.

In the first phase of this study, the impact of different parameters (orientation, temperature set points (TSP) and natural ventilation) is analysed. In the second phase, the impact of building envelope retrofit strategies (addition of extra insulation, retrofit of windows, etc.) is studied and compared with the impact of changes involving more fundamental architectural transformations like e.g. the use of solar shading devices, the addition of thermal mass or adding a second floor or adjacent house (doubling urban density), etc.

These retrofit strategies have the potential of improving the life quality of the occupants and reduce operation costs, which may also increase the economic value of the bungalows. It is also expected that retrofit strategies involving architectural transformations may also improve the urban density and quality. All this may encourage young families to move to these older suburbs instead of buying new houses on the outskirts of the city.

As stated, this paper presents the results of the first phase of the study: these results concern mainly the validation of the base case model with data about the measured energy intensity found in existing databases.

METHODS

This study was carried out by using dynamic energy simulations with the program DEROB-LTH (version 2.0), developed at Lund University, Sweden. A representative model of a bungalow house was built in the program, based on an analysis of 82 construction permits of existing bungalows located in Quebec City. The permits included floor plans, elevations, sections and construction details. A base case simulation of the typical bungalow enabled the comparison of energy use for heating with data provided by the Agence de l'Efficacité Énergétique of the province of Quebec (Légaré, 2007) for 1003 bungalows. This database allowed an initial validation of the base case model. The base case model of the typical bungalow was then used for evaluating the impact of orientation, temperature set points and natural ventilation on energy efficiency and thermal comfort.

Presentation of DEROB-LTH

DEROB-LTH, which stands for dynamic energy response of buildings-Lund Tekniska Högskolan, is a detailed iterative dynamic energy simulation program, which has been validated with measurements under natural climate [5]. The program was initially created as DEROB at the Numerical Simulation Laboratory of the University of Texas, Austin. Since the 1980s, it has been further developed as DEROB-LTH at Lund University, and is still continuously developed as a research tool [6, 7]. DEROB-LTH performs simulations allowing the study of the energy performance of buildings for various designs [8]. A simulation can generate numerous hourly results such as annual energy demand and peak loads for heating and cooling, comfort indices (PMV, PPD) and indoor, surface and operative temperatures (OT).

Building and Model Description

The bungalow (Fig. 1) is a one story building (ground-floor) with an inhabited basement. The plan is organized in order to segregate private and public activities. The first-generation of bungalow houses in Quebec are very uniform although there is a great amount of variations due to the fact that they were built by small property developers [9]. For this reason, it was imperative to analyze different first-generation bungalows in order to figure out what represents a typical case.

A total of 82 construction permits, provided by the GIRBa (Groupe interdisciplinaire de recherche sur la banlieue, Després, 2007) of Université Laval, were analyzed according to numerous criterions, such as year of construction, area, orientation, plan, materials, window superficies, etc. One of the permits was selected as representative of the typical bungalow (Fig. 2).

A model of the typical bungalow was built in DEROB-LTH. It contained six volumes (four on the ground-floor: living-room, kitchen and dining-room, restroom, laundry and study, master bedroom and bedroom; one in the basement and one in the attic). The total floor area is 186m^2 (93m^2 per floor) and the window area is 17% of that area. The different building elements of the model were assigned to corresponding typical wall-roof-floor-door assemblies of materials. The U-values of these assemblies were adjusted in order to take into account thermal bridges through structural elements and window frames (see Table 1). The base case model has an infiltration rate of 0.36 ach. This value was determined according to the air change rate data provided by Van Ryswyk (2008) of Health Canada. This data is based on actual measurements in Canadian single-family houses which were built from 1949 to 1989. The high air change rate value indicates that the building is not sufficiently airtight and that no mechanical ventilation is necessary as it stands.
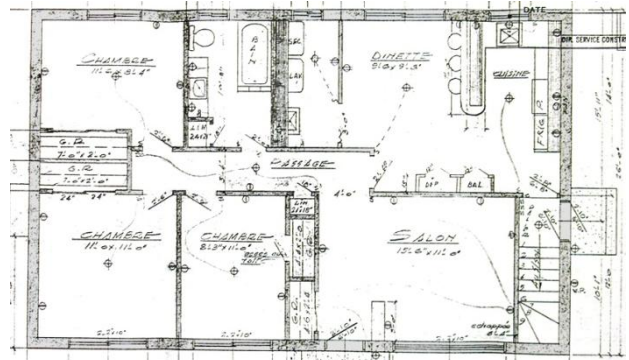

Figure 2: Ground-floor plan of the typical bungalow
(From construction permit, Després, 2007)

Table 1: U-values of the building elements

Typical assemblies	U-values (W/m^{2}K)
External walls (stone/wood)	0.47 / 0.42, 0.44, 0.89, 0.62
Internal walls	2.15, 2.24
Roof	2.55
Ceiling	0.37
Floor	1.10
Basement floor	4.43
Groundwork (above/undergr.)	1.88 / 1.91
Doors	1.10
Glazing (double-pane)	2.88

Figure 1: A typical bungalow house in Quebec, Quebec City
(photo : Jean-Philippe Saucier)

In a building, a significative amount of heat is constantly generated by internal heat sources. These sources can be sorted according to three categories: occupants, artificial lighting and equipments [11]. The internal loads are not dependent of the external climate or the building itself; they are a property of the occupants, their habits and their schedules [12, 13]. Some assumptions about the family occupying the typical bungalow were made in order to estimate internal loads. We assumed that a family of three persons lived in the house: two working adults and their child, a schoolboy. These inhabitants generate different quantity of body heat accordingly to their sex or age [14]. They are all assumed to be at home more frequently during weekends (19h) than during weekdays (15h). Internal heat gains were also estimated according to the season, summer and winter. It was considered that 95% of the energy used by lamps is emitted as heat [13] and that all the light sources were incandescent lamps. This was assumed although Canadian statistics on lighting indicate that around 77% of light sources are incandescent [15]. The total summer (June, to August) internal loads summed up to 20.8 kWh/day during the week and 24.1 kWh/day during the week-end. The total winter (September to May) loads summed up to 21.1 kWh/day during the week and 24.3 kWh/day during the week-end. This is in line with the 20 kWh/day standard proposed by the Office of Energy Efficiency [16].

Considering the fact that the building elements (walls) of the model do not have a thickness, the windows simply consist of a hole in the building elements filled with a flat surface considered as a double pane window. The lack of depth in the model, around the windows, was compensated for by the addition of shading screens around windows. Shading screens were also added on the outskirts of the plot for lateral neighbours in order to simulate the impact of shading from the neighbouring houses.

Simulations with DEROB-LTH
The 82 bungalows associated with the construction permits analyzed are all located in Quebec City. The climate file for Quebec City for year 1995 was thus used for the simulations. This year is considered as a TRY (test reference year). The climate file was provided by Concordia University, Montreal (Zmeureanu, 1998).

The base case model used for validation was oriented due south. The temperature set points were 19-21°C, which is according to a survey by the Canada Mortgage and Housing Corporation [17]. No natural ventilation and no cooling system were assumed for the base case. Finally, the following parameters of the base case were varied: orientation, temperature set-points and natural ventilation schedule (see Table 2).

Table 2: Plan of the parametric study (base case)*

Orientation	Temperature Set Points (°C)	Natural Ventilation
South*	19-21*	No*
South-East	19-21	No
South-West	19-21	No
North-East	19-21	No
North-West	19-21	No
South	*17-21*	No
South	*21-23*	No
South	19-21	*Night (23/24-7h/9h)*
South	19-21	*Afternoon (12-19h/20h)*
South	19-21	*Day (24h)*

RESULTS
The results of the simulation for the base case show that the annual heating energy demand (AHED) sums up to 20358 kWh/year (109 kWh/m^2,yr). When compared with data measured in single-family housing in Canada and Quebec (see Table 3), the heating load of the base case is generally too low. This could be explained by numerous factors, such as discrepancies regarding internal loads, temperature set points and thermal bridges and losses that occur at the corners of the house (since the computer program is in one dimension, two- and three dimensional thermal bridge effects are not accounted for).

Table 3: AHED (kWh,yr) and heating energy intensity (kWh/m^2,yr) in Canada and Quebec for single-family housing

Sources	Annual heating energy demand (kWh/yr)	Heating energy intensity (kWh/m^2,yr)
[15]	-	157 175 191
[3]	25116	127
[20]	21166* 23833**	- -
[21]	-	136
[22]	-	156

* Province of Quebec
** Canada

An analysis of operative temperatures for the base case indicates a great risk for overheating (>26°C) in the summer as well as in the winter. The areas at risk for overheating are the living-room, where the largest window is located and the kitchen and dining-room, where most of the internal heat gains sources are. From Jan. to May, the OT is above 26°C 4.4% of the time in the living-room, kitchen and dining-room; 67.2% and 70.0% of the time from June to Aug. and 9.0% and 7.8% from Sep. to Dec. in the living-room and kitchen-dining-room respectively. The base case results thus indicate that overheating should be reduced or eliminated and that

passive cooling strategies should be use to improve thermal comfort. Volume 2 (kitchen and dining-room) is the volume where the operative temperatures are the highest (40.0°C). Volume 2 will thus be studied more thoroughly according to overheating discomfort indices.

The temperature set points entered in DEROB-LTH secure indoor air temperature above 19°C or 21°C. However, thermal comfort (operative temperatures) results indicate that the OT drops below 19°C quite often. Volume 4 (bedrooms) and 5 (basement) are the volumes where this phenomenon occurs most often, because the temperature set-point is always kept at minimum in volume 4 (19°C) and because basements are always cooler. Volume 4 (bedrooms) will thus be studied more thoroughly according to winter (cold) discomfort.

Orientation and Energy-Efficiency
Figure 3 presents the results of the base case model according to different orientations. It shows that the variation of the orientation has a negligible effect on annual heating loads. Fig. 3 indicates that the south orientation (base case model) is the most energy-efficient while the north-east orientation is the least energy-efficient when comparing heating loads.
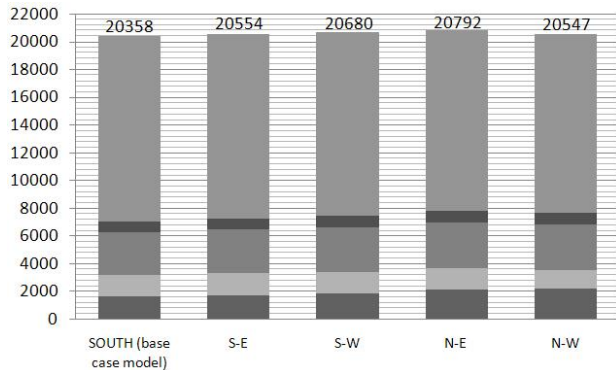

Figure 3: AHED (kWh) per volume (V5(basement) at the top and V1(living-room) at the bottom); summing up to AHED (kWh); according to different orientations

A close analysis of Fig. 3 indicates that the windows on the south facade contribute to reduce heating for south rooms while windows on the north facade increase heating for north rooms in the south orientation case. When the model is rotated towards north-west, the same effects can be observed, which explains why orientation has little effect on the heating demand. Windows on opposite sides create counterbalancing effects. In order to see an effect of orientation, the architecture of the building (including position of windows and roof shape, etc.) needs to have a predominant orientation (towards the south to increase passive solar gains with few windows on the north facade).

Orientation and thermal Comfort
Figure 4 presents the OT results for volumes 2 (kitchen and dining-room) and 4 (bedrooms) of the base case according to different orientations. It shows that the south orientation is preferable. The number of hours with overheating or winter (cold) discomfort are inferior in both volumes for the south orientation compared with the four other tested. When analyzing the max. and min. OT, the south orientation is still preferable. The variation of orientation does not have a significant impact on extreme OT, but it has a significant effect on the number of hours when the house is thermally comfortable.
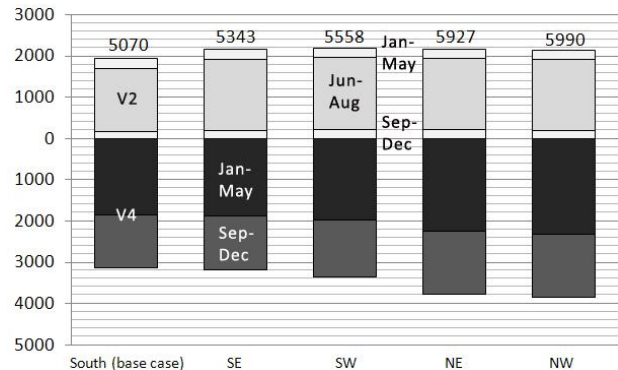

Figure 4: No. of hours when the OT is >26°C in V2 (kitchen and dining-room) (light grey) and no. of hours when the OT is <19°C in V4 (bedrooms) (dark grey); summing up to the no. of hours when the OT is <19°C or >26°C; according to different orientations

Temperature Set Points and Energy-Efficiency
Figure 5 presents the results of the simulations for the base case according to different TSP. It indicates that, contrarily to the orientation, the variation of this parameter has a significant effect on the energy demand. A reduction of 2°C can generate major savings (-13%) in terms of heating energy demand compared with the base case TSP of 19-21°C. Inversely, an increase of 2°C can yield a significant increase (+14%) in heating energy use.
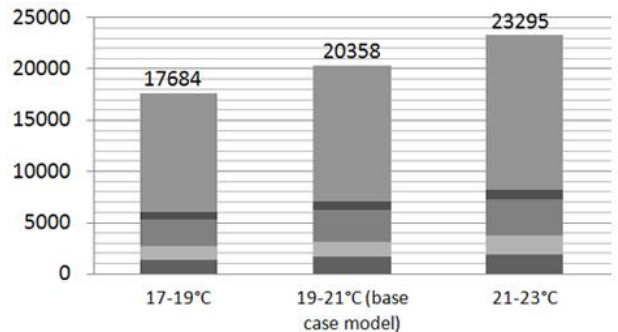

Figure 5: *AHED (kWh) per volume (V5(basement) at the top and V1(living-room) at the bottom); summing up to AHED (kWh); according to different temperature set points*

Temperature Set Points and Thermal Comfort
Figure 6 presents the OT results for V2 and V4 according to various TSP. It shows that the 17-19°C TSP causes less overheating but much more winter (cold) discomfort. It also indicates that although the 21-23°C set point solution creates an increase in the number of hours of overheating, the house is more often thermally comfortable than in the two other solutions.
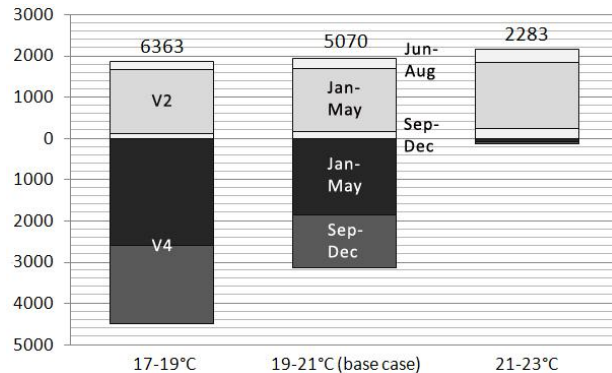

Figure 6: No. of hours when the OT is >26°C in V2 (kitchen and dining-room) (light grey) and no. of hours when the OT is <19°C in V4 (bedrooms) (dark grey); summing up to the no. of hours when the OT is <19°C or >26°C; according to different temperature set points

Natural Ventilation
In DEROB-LTH, it is possible to simulate open windows according to a fixed schedule. This has some perverse effects: if opened windows are specified in summer, this will result in an increase in the heating demand due to some cold days in this time period. For this reason, we analyzed the effect of natural ventilation only during a typical hot summer day (6th of July: cool at night (min. 20.9°C) and hot during the day (max. 30.9°C)).

The operative temperature results for volume 2 on a typical hot summer day according to different natural ventilation schedules indicate that night ventilation can significantly reduce the number of hours (17h) of overheating compared with the base case (24h). On the other hand, afternoon ventilation does not reduce the number of hours of overheating (24h). However, the lowest maximum operative temperature occurs when ventilating during the afternoon (33.6°C), not during the night (36.7°C). The best solution comes from all day ventilation (24h): the number of overheating hours drops down to 13h and the maximum operative temperature to 31.1°C. This result indicates that using night ventilation as a passive cooling strategy is not the best solution: constant ventilation is preferable. This result is counter intuitive and needs to be analyzed further.

DISCUSSION
Regarding orientation, the results have shown negligible effect of building orientation on heating loads. This is explained by the fact that openings are almost symmetrical (both on south and north side). In order for orientation to contribute to passive heating, it is essential that the openings be dominantly located on the south side (with fewer openings on other sides, particularly on the north facade). In future simulations, a model where south side openings are increased while north side openings are reduced will be tested.

The results are not so straightforward when it comes down to temperature set points: lower (17-19°C) set points are more energy-efficient, but higher (21-23°C) set points are more thermally acceptable for the occupants since the winter discomfort phenomenon nearly vanishes, even though overheating occurs more often. The TSP of 21-23°C will be used since thermal comfort should predominate on energy efficiency and considering that this will not affect the validity of the second phase results which will be based on comparison and relativity.

The results regarding natural ventilation strategies are somewhat confounding. We expected that a night ventilation schedule would yield great improvements in terms of operative temperature reduction. This was not the case: we observed that an all-day ventilation strategy yields a better performance. This may be due to the fact that the afternoon solar gains cannot be lost to the outside when the room is closed during the afternoon (as in the case of the night ventilation strategy). This certainly indicates that a night ventilation strategy needs to be combined with solar shading and/or thermal mass. Solar shading will reduce solar gains in the afternoon and thermal mass will store heat during peak periods. These hypotheses will be tested in the second part of the study and it is expected that, in that case, night ventilation combined with solar shading and thermal mass will be more effective than an all-day ventilation strategy.

These previous observations could easily be transferred to other housing types in northern climate: it is clear that good orientation and natural ventilation cannot generate the best performances if they are not integrated with other passive strategies. In the case of the TSP, we could add that major energy savings could be obtained in cold regions housing if the occupants would be willing to accept important habit changes such as wearing warmer clothes inside during winter: warmly wrapped up, the occupant could accept lower indoor operative temperatures. A 17-21°C temperature set points could thus represent an acceptable solution in terms of thermal comfort while allowing big heating energy demand reductions.

CONCLUSION

This paper presented the results of the first phase of simulations in a Master's thesis concerning retrofit strategies of the first generation of bungalow houses in Quebec. The first results indicate the following:

- The base case model of the bungalow house has an energy intensity of 109kWh/m^2,yr, which is slightly below the data measured for 1003 bungalows in Quebec (127 kWh/m^2,yr according to the Agence de l'efficacité énergétique's database). The discrepancy between the model and the database is explained by differences regarding thermal bridges, TSP, infiltration rates, etc., between the computer model and a real building.
- The bungalow house does not have a high performance in terms of thermal comfort: overheating and many hours with a risk for winter (cold) discomfort are experienced.
- Temperature set-points of 21-23°C causes a significant increase in heating demand but considering that it increases considerably thermal comfort, it should thus be maintained in all future simulations.
- The night ventilation strategy has proved to be less effective than an all-day ventilation strategy. The results generally show that the ventilaiton strategy needs to be combined with other passive measures such as e.g. the use of thermal mass and solar shading. This result only emphasizes the importance of integrated design.

Finally, the second phase of this study will be presented in a future paper. Isolated and combined effects of passive strategies will be assessed. We expect to find that passive strategies are sufficient for reducing heating loads significantly and improving thermal comfort without the use of artificial air-conditioning machines.

ACKNOWLEDGMENTS

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