Quantification of teleworking impact on energy consumption and thermal comfort in residential buildings

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Abstract

Canadian residents routinely adjust their thermostat up in the summer and down in the winter when they are away for more than a few hours to help to save energy. In the case of teleworking, some energy may be wasted as the remaining spaces in the home are unoccupied. This paper aims to quantify the energy consumption and thermal comfort of various HVAC control schemes. This work investigated the effect of using a smart thermostat for multiple teleworking scenarios. Findings indicated that teleworking increased the building energy consumption by 4% maximum, whereas it increased the thermal discomfort by 54% maximum.

Introduction

After the Covid-19 pandemic caused lockdowns and capacity reduction at workplaces, the world experienced a shift from working from offices towards working remotely as a teleworker. Teleworking is defined as working outside of the assigned office for the job from one day (part-time) to five days (full-time) a week.

Many Canadian homes are heated and cooled with a central heating, ventilation, and air conditioning (HVAC) system that works based on on/off controls. By adjusting the HVAC thermostat setpoint upwards in the summer and lower in the winter when residents are away for more than a few hours, they can help to save energy. In the case of teleworkers, as probably not all the occupants can work from home, some energy may be wasted since the remaining spaces in the home are unoccupied. The effect of teleworking on energy use and greenhouse gas (GHG) emissions should be investigated in four main domains: offices, residential buildings, transportation, and information and communication technologies (ICT) (O'Brien and Aliabadi, 2020). Previous research has focused mainly on the effect of telework on office buildings and transportation, while residential buildings have been less studied. As a result, the overall energy implications of telework considering all four main domains are not clear (Larson and Zhao, 2017).

Residential buildings consume approximately 17% of primary energy resources in Canada (NRCan, 2021). Therefore, investigating the energy change in residential buildings due to teleworking plays a crucial role in quantifying the effect of teleworking on total energy use in Canada and understanding and predicting future trends in energy use, and adapting policy (building codes, retrofit incentives, etc.). Roth, Rhodes, and Ponoum (2008) made simple assumptions about residential lighting and HVAC energy use without considering how the occupant's presence could affect thermostat setpoints. An Australian study indicates that a family with full-time jobs and no teleworking days has the lowest annual cooling and heating demands in a building model compared to families with full-time or partial-time teleworkers at home (Jazaeri, Gordon, and Alpcan, 2019).

Previous work did not focus on the details and nuances of building performance, considering the implications of HVAC controls, zoning, and thermal comfort. Furthermore, there is a gap in the investigation of using different HVAC control configurations for different teleworking scenarios. For example, because not all people who telework live alone, there is the possibility of overestimating home energy consumption change (Röder and Nagel, 2014). Therefore, teleworking scenarios in families with a permanent daytime resident (e.g., a retired grandparent) should be explored. In the cases that office space is not changed, and the teleworker is not alone at home on teleworking days (there is a permanent daytime resident other than the teleworker at home), telework does not have a remarkable effect on energy use as the energy consumption in the office is not reduced, and the increase in energy consumption at home is slight (Nakanishi, 2015). Moreover, using national statistics, Matthews and Williams (2005) and Röder and Nagel (2014) estimated home energy consumption increase due to teleworking in the United States and Japan. Sun Microsystems (2009) calculated the energy use increase at home by distributing measuring devices to teleworkers.

The literature needs to quantify energy change due to teleworking by using a parametric house model concerning occupant behavior and the use of a thermostat that controls the HVAC system dynamically (smart thermostat) in adaptivity to partial occupancy. Furthermore, in most studies, the number of teleworking days in a week, house model and characteristics, and HVAC control configuration is not distinct. The objective of this paper is to quantify the energy consumption of homes and occupant's thermal

comfort due to partial teleworking (one day per week in this paper) and full-time teleworking. Also, this study tried to answer this question: Is it beneficial to control the house as a two-space area with a smart thermostat to adapt to partial occupancy such as teleworking?

Research methodology

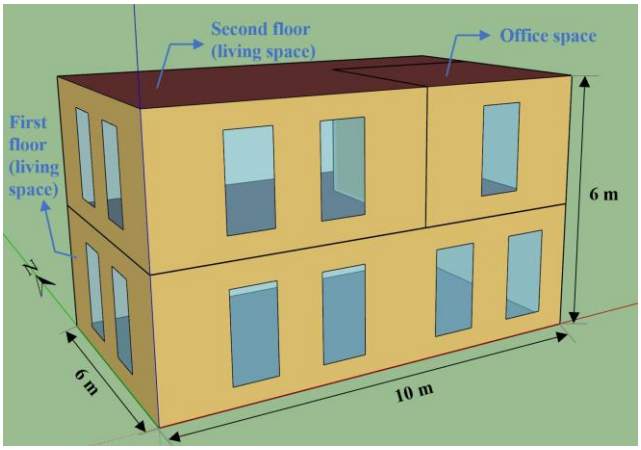
To address the lack of research on residential building performance and occupant thermal comfort under partial occupancy, the current study presented a simulation-based investigation of 24 different teleworking scenarios and 24 baseline scenarios (no teleworker at home). All simulations are done by EnergyPlus software version 9.5 (DOE, 2020).

Building models

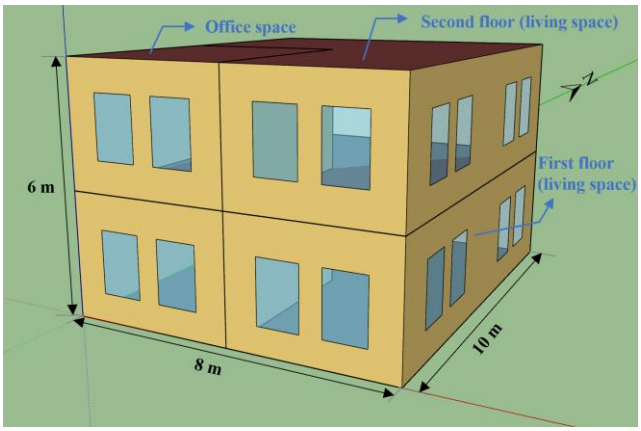
Based on a survey that Natural Resources Canada implemented in 2015 (NRCan, 2015), Canada's most common type of dwelling is a two-storey single-detached house. The primary energy source used for heating is natural gas and electricity for cooling. This survey also shows that typical double-pane glass is the most common window type. A detached, two-story house was selected as a typical building model for the simulation.

Two building models regarding the number of thermal spaces were selected to find the effect of using a smart thermostat on energy consumption and occupant's thermal comfort. The first building model is called the *single-space* building, where the entire house is treated as one thermal space. The second building model is called the *two-space* building, where one space is the office that is defined as occupied by the teleworker between 8 AM and 5 PM one day or five days a week, and the other space is the rest area of the building that is called the living space. In this study, the *two-space* building is divided into two thermal spaces so that air temperature can be monitored in both the office and the remainder of the house. However, it is controlled as a single thermal zone because we only have one HVAC system for the entire house, and we use a constant air volume system (CAV) which supplies constant airflow at a variable temperature, as the most common system in residential buildings. Teleworking scenarios in the *two-space* building model and *single-space* building model are compared to provide evidence for the question of whether homes should start using a smart thermostat with multiple spaces to adapt to partial occupancy.

Additionally, this study selected two building models in terms of building total area to cover more types of dwellings in Canada. The first building model is 120 m^2 with an office space of 16 m^2, and the second building model is 160 m^2 with an office space of 20 m^2. The windows in both models are typical double-pane glass, and the office's windows are south-facing. Figure 1 shows the house model geometries used in this study. Other characteristics of the building models can be found in Table 1. The window-wall ratio in this table was calculated by dividing the total area of the windows by the total area of the walls.



(a)



(b)

Figure 1: Two-space building models. (a)120 m^2 model, and (b)160 m^2 model

Climate zone

To see the effect of climate on energy use and conduct a more comprehensive investigation, three Canadian cities are selected: Vancouver (climate zone 4), Ottawa (climate zone 6), and Edmonton (climate zone 7A). The National Energy Code of Canada for Buildings 2017 (NECB) is used to model envelopes for each climate zone's building models (NECB, 2017). Table 2 shows the R-value and U-value for walls, foundation, and roof of building models in three Canadian climates based on their heating degree days (HDD), with 18˚C being the base temperature. Cooling months in this table are chosen based on the weather data for each city. Eight scenarios in each city are simulated in the 120 m^2 building model and eight in the 160 m^2 building model.

Occupancy scenarios

Each city has 16 scenarios, half of them are defined to have a daytime resident (other than the teleworker), and the other half are defined without a daytime resident. A daytime resident is a person who does not leave the house regularly for a job (e.g., a retired grandparent) and is assumed to be in

Table 1: House model geometry specification

	Total area (m^2)	Office area (m^2)	Total window-wall ratio (WWR)	Office WWR	Living space WWR	Office window facing	Living space window facing
Building model 1	120	16	0.23	0.17	0.23	South	South and West
Building model 2	160	20	0.30	0.34	0.29	South	South and East

the living space in *two-space* building models. Three types scenarios are chosen to find the effect of the number of teleworking days: no teleworker at home (baseline), a teleworker who works from home one day a week, and a teleworker who works from home five days a week. In all scenarios, office hours are considered between 8 AM and 5 PM.

HVAC control

The heating and cooling setpoints were 22˚C throughout the day in all scenarios. For energy-saving purposes, the setpoint during the heating season is adjusted to be 18˚C, and during the cooling season is adjusted to be 25˚C throughout away hours. Also, the setpoint at night in the winter is 18˚C. The HVAC system is an air handling unit (AHU) that uses natural gas for heating and electricity for cooling. Ventilation is 0.014 m^3/s and 0.04 m^3/s for the office and the living space, respectively (ANSI/ASHRAE, 2019). It should be noted that simultaneous heating and cooling is not defined for the building models in this paper. Cooling months are implied in Table 2 for each climate zone, and the HVAC system is always available in all scenarios.

Occupancy-based thermostat setpoint

A smart occupancy-based thermostat is used to divide the area of the *two-space* building model into master and slave zones. The master zone is the main zone where the HVAC system is trying to keep the temperature of this zone at the defined setpoint. Smart thermostats usually have occupancy detection sensors and can switch the master and the slave zones based on occupancy to save energy when the house is not fully occupied. Heating and cooling energy are provided based on the master zone temperature and according to the seasonal schedule for the entire building area (i.e., heating and cooling are not provided on the same day, and we defined specific cooling and heating months for each climate zone). The master zone is the office during the office hours that the teleworker occupies this space. In this case, the living space is the slave zone, whether it is occupied by a daytime resident. It means that if the temperature of the occupied office deviates from the setpoint (22˚C), the HVAC system will be turned on to serve the spaces whether the slave zone needs conditioning or not. The smart thermostat changes the master zone when the office hours end and the teleworker leaves the office. In this case, the occupied living space is the master zone, and the HVAC system tries to keep the temperature of this space at the setpoint.

Energy Management System

HVAC systems are sized using design conditions, extreme conditions that occur only a small percentage of time each year. As a result, HVAC systems frequently operate at part-load conditions since their capacity is larger than necessary except in the most extreme weather conditions. Most HVAC systems for residential and small commercial buildings use on/off controls. However, most energy modeling software tools such as EnergyPlus do not simulate the on/off nature of this type of HVAC control (Cetin, Fathollahzadeh, Kunwar, Do, and Tabares-Velasco, 2019).

The energy management system (EMS) in EnergyPlus was used to simulate the on/off control for the HVAC system of the models. A very high (50˚C) and a very low (10˚C) setpoint were used to turn the system fully on or off because EnergyPlus calculates the HVAC system's load based on the delta in setpoint and air temperature (Cetin, Fathollahzadeh, Kunwar, Do, and Tabares-Velasco, 2019). In other words, EMS creates a new setpoint and overrides the previous setpoint to make the system fully on or fully off based on the current temperature in the master zone. For example, in the winter, when the teleworker is at home during office hours, the main zone is the office, and the HVAC system works based on the temperature of this space. If the current temperature in the office falls below the daytime setpoint (22˚C), the EMS changes the HVAC setpoint temperature to 50˚C (new setpoint). As the current temperature is far less than the new setpoint, the HVAC system is turned on with full capacity and increases the room temperature. As soon as the temperature in the office exceeds 22˚C, the EMS sets the setpoint at 10˚C, and since the current temperature is higher than the new setpoint, the HVAC system will be turned off. This process repeats if the temperature falls below 22˚C. The same HVAC control system operates for the living space during the hours that this space is the master zone. It should be mentioned that this process is done in ten minutes timesteps for all simulations.

Thermal comfort

This study calculated thermal discomfort by adding the temperature differences between the current and setpoints for both thermal spaces. In this work, tolerance of ±0.5˚C was considered. For example, in the winter, when the setpoint is 22˚C, all temperature data below 21.5˚C or above 22.5˚C were added to calculate thermal discomfort for both spaces.

Table 2: Technical house model specification for each city

	HDD (˚C·day)	Climate zone	Cooling months	Windows U-value (W/(m²·K))	Windows SHGC	Walls R-value (m²·K/W)	Foundation U-value (W/(m²·K))	Roof U-value (W/(m²·K))
Vancouver BC	< 3000	4	Mid-May until mid-September	2.1	0.31	0.315	0.757	0.193
Ottawa ON	4000-4999	6	Mid-May until mid-September	1.9	0.31	0.247	0.757	0.156
Edmonton AB	5000-5999	7A	Mid-June until mid-August	1.9	0.31	0.210	0.757	0.138

Results

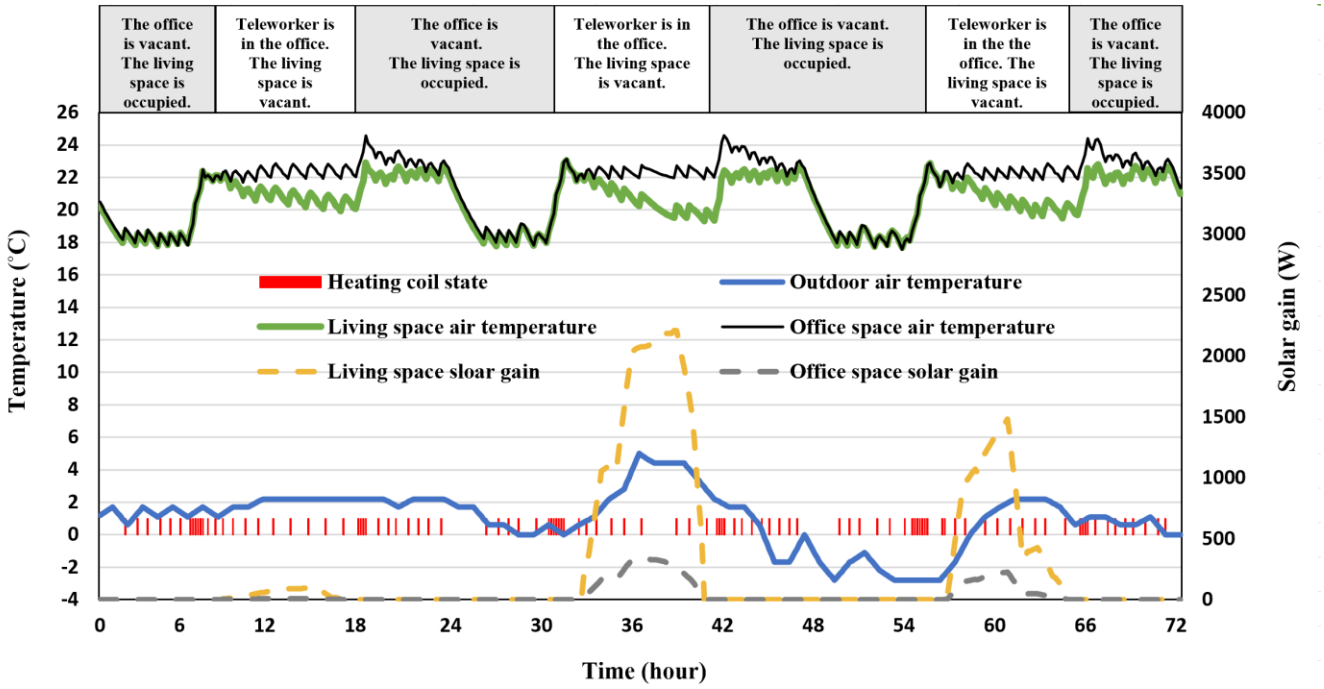
Temperature profiles for the scenario that has a full-time teleworker in Vancouver without a daytime resident (scenario 7) are shown in Figure 2 for both spaces over three working days. Figure 2 (a) shows these changes for three weekdays in a row with different solar gains in the winter. On all three days during office hours, the solar gain in the office maintains this space's air temperature above the desired setpoint (22˚C) for much of the day. Because the HVAC system of the building is controlled based on the office air temperature when this space is occupied, the HVAC system is not turned on for extended periods. The result is a significant drop in temperature in the living space since it does not experience as high solar gains relative to its size. In the scenarios that we have a daytime resident in the living space, this temperature drop can be a source of thermal discomfort for the daytime resident during office hours.

Figure 2 (b) also shows temperature profiles for three weekdays in a row in the summer for scenario 7. In this case, the living space is over-cooled during office hours because the office has a south-facing window and gets considerable solar radiation relative to its size. As a result, the HVAC system should be turned on for extended periods and more frequently to keep the office temperature at 22˚C. So, when the office is occupied, the living space, the slave zone, is forced to receive cooling energy during these periods without needing it. This phenomenon can be an important source of thermal discomfort for the daytime resident during office hours in the summer.

Annual heating energy, cooling energy, total energy intensity, and thermal discomfort are calculated for all 48 scenarios and are shown in Table 3, Table 4, and Table 5. The total energy use intensity shows the building model's overall energy use per area, including lighting and fan energy. The result shows that five days of teleworking per week increased the total building energy use intensity by 4% maximum compared to zero days of teleworking in the same *two-space* building model. This increase happened in the 120 m^2 building model in Edmonton without a daytime resident at home (scenario 39). Moreover, one day of teleworking per week increased the total energy use intensity by 1% maximum. This energy increase happened in the 160 m^2 model in Edmonton without a daytime resident at home (scenario 45).

On the other hand, the results indicate that if the building has a daytime resident, teleworking can save energy in many scenarios. The maximum energy use decrease happened in the scenario with a full-time teleworker and a daytime resident in the 120 m^2 building model in Edmonton (scenario 40) by 4%. Comparing the tables of the results suggests that in most of the scenarios without a daytime resident, teleworking increased the energy consumption of the building, whereas it decreased this energy in scenarios with a daytime resident regardless of climate zone or building area. The energy decrease in scenarios with a daytime resident and a teleworker (even number scenarios) happened because the HVAC system worked based on the office temperature during office hours. As explained in Figure 2, since the office gets more solar energy compared to its area than the living space, the heating energy consumption decreases, and the cooling energy consumption increases compared to the baseline scenario when the HVAC system worked based on the living space. As a result, because the heating energy consumption is dominant, a total energy use reduction compared to the baseline happened.

Calculating thermal discomfort indicates that adding the number of teleworking days increased the thermal discomfort for the occupants. Furthermore, scenarios with a daytime resident had more thermal discomfort than scenarios without a daytime resident. As a result, the highest thermal discomfort in each building model in every climate zone happened for the scenario with a full-time teleworker and a daytime resident. Comparing the energy consumption change and thermal discomfort change for scenarios with a daytime resident suggests that although teleworking saved energy in these scenarios (by 4% maximum), it significantly decreased the thermal comfort. Thermal discomfort due to teleworking increased by 54% maximum compared to zero teleworking days in the *two-space* building model. This increase happened for the full-time teleworking scenario with a daytime resident in Ottawa for building model 120-m^2 (scenario 24). This research also tried to answer this question: Is it beneficial to control the house as a two-space area with a smart thermostat to adapt to partial occupancy



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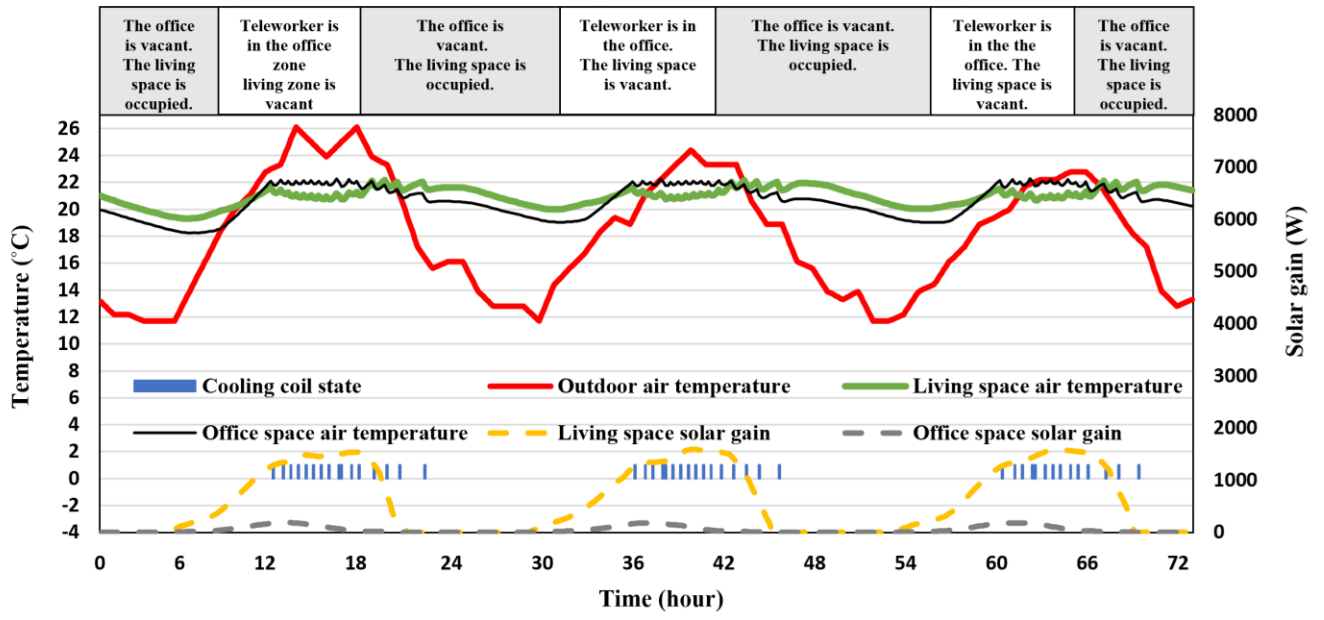

(b)

Figure 2: Temperature change in the office and the living space during three days of teleworking in the two-space 120 m^2 building model in Vancouver: (a) January and (b) July

such as teleworking? To answer this question, we compared the total energy use intensity results for a single-space building model with a daytime resident (this daytime resident can be the teleworker, e.g., in scenario 2 or 7 for Vancouver) with the scenario that has a teleworker in a two-space building model without any other daytime residents for each building area and each climate zone. For example, scenario 34 in Table 5 represents the case that the building is controlled as a single-space house, and a person wants to stay at home during office hours to telework five days a week. Alternatively, scenario 39 represents the condition that this building is controlled as a two-space house, and the full-time teleworker from scenario 34 can use just one space (the smaller space in this research) during office hours. In

Table 3: Annual building energy consumption and thermal discomfort for Vancouver scenarios

City-Building area	Scenario number	Number of spaces	Teleworking days	Daytime resident (other than the teleworker)	Office heating energy (kWh)	Living heating energy use (kWh)	Office cooling energy (kWh)	Living cooling energy (kWh)	Building total heating energy (kWh)	Building total cooling energy (kWh)	Building total energy intensity (kWh/m^2)	Building total energy change compared to the one-space building (%)	Building total energy change compared to the two-space building (%)	Thermal discomfort (×10^3 °C. hour)	Thermal discomfort change compared to the one-space building (%)	Thermal discomfort change compared to the two-space building (%)
Vancouver-120 m^2	1	1	0	No	-	-	-	-	17,400	1,140	215.2	-	-0.8	4.8	-	0
	2			Yes	-	-	-	-	18,110	1,320	228.5	-	-0.3	5.5	-	0
	3	2	0	No	2,480	14,930	150	1,000	17,410	1,150	216.9	0.8	-	4.8	0	-
	4			Yes	2,620	15,500	150	1,180	18,120	1,330	229.3	0.4	-	5.5	0	-
	5		1	No	2,500	14,950	160	1,040	17,450	1,200	217.4	1.0	0.2	5.0	3	3
	6			Yes	2,600	15,430	180	1,170	18,030	1,350	228.0	-0.2	-0.6	5.8	6	6
	7		5	No	2,510	15,280	190	1,160	17,790	1,350	222.6	3.4	2.6	6.0	24	24
	8			Yes	2,490	15,040	200	1,250	17,530	1,450	224.3	-1.8	-2.2	7.3	33	33
Vancouver-160 m^2	9	1	0	No	-	-	-	-	18,360	1,030	171.2	-	-0.7	4.8	-	0
	10			Yes	-	-	-	-	18,040	1,290	178.4	-	2.5	5.3	-	7
	11	2	0	No	2,600	15,780	150	850	18,380	1,000	172.4	0.7	-	4.8	0	-
	12			Yes	2,530	15,360	190	1,100	17,890	1,290	174.0	-2.5	-	5.0	-6	-
	13		1	No	2,580	15,680	160	970	18,260	1,130	172.0	0.5	-0.2	5.0	3	3
	14			Yes	2,540	15,360	180	1,140	17,900	1,320	177.7	-0.4	2.1	5.7	6	6
	15		5	No	2,510	15,480	200	1,200	17,990	1,400	173.5	1.3	0.6	5.8	21	21
	16			Yes	2,470	15,130	210	1,280	17,600	1,490	175.1	-1.8	0.6	6.8	28	28

Table 4: Annual building energy consumption and thermal discomfort for Ottawa scenarios

City-Building area	Scenario number	Number of spaces	Teleworking days	Daytime resident (other than the teleworker)	Office heating energy (kWh)	Living heating energy (kWh)	Office cooling energy (kWh)	Living cooling energy (kWh)	Building total heating energy (kWh)	Building total cooling energy (kWh)	Building total energy intensity (kWh/m^2)	Building total energy change compared to the one-space building (%)	Building total energy change compared to the two-space building (%)	Thermal discomfort (×10^3 °C. hour)	Thermal discomfort change compared to the one-space building (%)	Thermal discomfort change compared to the two-space building (%)
Ottawa-120 m^2	17	1	0	No	-	-	-	-	24,360	1,920	291.4	-	-0.2	4.2	-	14
	18			Yes	-	-	-	-	24,800	2,150	302.2	-	-0.2	4.8	-	4
	19	2	0	No	3,450	20,940	260	1,670	24,390	1,930	291.9	0.2	-	3.7	-12	-
	20			Yes	3,520	21,390	280	1,880	24,910	2,160	302.9	0.2	-	4.7	-3	-
	21		1	No	3,440	20,950	260	1,700	24,390	1,960	293.2	0.6	0.4	4.5	8	23
	22			Yes	3,500	21,260	280	1,890	24,760	2,170	301.7	-0.2	-0.4	5.3	10	14
	23		5	No	3,420	21,230	290	1,810	24,650	2,100	297.3	2.0	1.8	5.5	32	50
	24			Yes	3,390	20,900	310	1,950	24,290	2,260	298.6	-1.2	-1.4	7.2	48	54
Ottawa-160 m^2	25	1	0	No	-	-	-	-	26,910	1,930	241.0	-	-0.1	4.2	-	4
	26			Yes	-	-	-	-	27,170	2,300	249.3	-	0.6	4.5	-	4
	27	2	0	No	3,790	23,130	270	1,670	26,920	1,940	241.2	0.1	-	4.0	-4	-
	28			Yes	3,690	23,150	290	1,830	26,840	2,120	247.8	-0.6	-	4.3	-4	-
	29		1	No	3,800	23,130	280	1,760	26,930	2,040	242.4	0.6	0.5	4.3	4	8
	30			Yes	3,810	23,340	310	2,030	27,150	2,340	248.4	-0.4	0.2	5.0	11	15

	31		5	No	3,710	23,170	330	2,000	26,880	2,330	244.4	1.4	1.3	5.0	20	25
	32			Yes	3,680	22,880	340	2,120	26,560	2,460	246.2	-1.2	-0.6	6.3	41	46

Table 5: Annual building energy consumption and thermal discomfort for Edmonton scenarios

City-Building area	Scenario number	Number of spaces	Teleworking days	Daytime resident (other than the teleworker)	Office heating energy (kWh)	Living heating energy (kWh)	Office cooling energy (kWh)	Living cooling energy (kWh)	Building total heating energy (kWh)	Building total cooling energy (kWh)	Building total energy intensity (kWh/m^2)	Building total energy change compared to the one-space building (%)	Building total energy change compared to the two-space building (%)	Thermal discomfort (×10^3 °C. hour)	Thermal discomfort change compared to the one-space building (%)	Thermal discomfort change compared to the two-space building (%)
Edmonton-120 m^2	33	1	0	No	-	-	-	-	25,150	590	295.7	-	0	5.8	-	0
	34			Yes	-	-	-	-	27,320	680	324.3	-	-3.3	6.0	-	9
	35	2	0	No	3,290	21,870	60	530	25,160	590	295.8	0	-	5.8	0	-
	36			Yes	3,550	23,770	80	610	27,320	690	335.2	3.4	-	5.5	-8	-
	37		1	No	3,300	21,970	70	540	25,270	610	298.4	0.9	0.9	6.2	6	6
	38			Yes	3,530	23,680	80	610	27,210	690	323.6	-0.2	-3.5	6.5	8	18
	39		5	No	3,320	22,610	100	600	25,930	700	306.9	3.8	3.8	7.5	29	29
	40			Yes	3,450	23,490	110	660	26,940	770	322.0	-0.7	-3.9	8.3	39	52
Edmonton-160 m^2	41	1	0	No	-	-	-	-	27,000	520	238.5	-	0.1	5.7	-	13
	42			Yes	-	-	-	-	27,210	700	247.8	-	0	6.7	-	-7
	43	2	0	No	3,460	23,520	70	460	26,980	530	238.3	-0.1	-	5.0	-12	-
	44			Yes	3,610	23,590	80	630	27,200	710	247.8	0	-	7.2	8	-
	45		1	No	3,460	23,620	70	510	27,080	580	240.6	0.9	1.0	6.0	6	20
	46			Yes	3,500	23,620	90	630	27,120	720	245.3	-1.0	-1.0	6.8	2	-5
	47		5	No	3,470	24,080	100	640	27,550	740	245.8	3.1	3.1	7.0	24	40
	48			Yes	3,420	23,550	110	700	26,970	810	244.5	-1.3	-1.3	8.3	25	16

this case, instead of keeping the entire house at 22˚C, we kept the smaller part of the house at 22˚C (master zone), and the greater area (slave zone) receives heating or cooling energy whenever the master zone needs conditioning. Results suggest that in the case of partial occupancy such as teleworking, the two-space building model has less total energy use intensity than the single-space model. The maximum energy use intensity saving happened in scenario 34 in Edmonton compared to scenario 39 (baseline) by 5%.

Conclusion

This study aimed to quantify the effect of teleworking on energy consumption and thermal comfort in residential buildings. Additionally, this research tried to answer this question: Is it beneficial to control the house as a two-space area with a smart thermostat to adapt to partial occupancy such as teleworking? To achieve the research questions, energy consumption and thermal comfort for 24 teleworking scenarios and 24 baseline scenarios in three Canadian climate zones for two building models in terms of the total area and two building models regarding the number of spaces in the house were simulated. In brief, the results indicated that energy consumption change due to teleworking depended on where a daytime resident was present at home. Teleworking in most of the scenarios with a daytime resident at home (other than the teleworker) did not increase the energy consumption compared to the baseline scenario (zero days of teleworking) and reduced energy consumption up to 4%. This maximum energy saving happened in the 120 m^2 building model in Edmonton with a daytime resident and a full-time teleworker. However, teleworking in this study significantly increased the thermal discomfort for the occupants since during office hours, the teleworker was in the office, the HVAC system worked based on this space's temperature, and the living space was forced to receive cooling energy without needing it or did not receive heating energy when it needed. Thermal discomfort due to teleworking increased by 54% at most, which occurred with the full-time teleworking scenario with a daytime resident in Ottawa for building model 120 m^2 (Scenario 24). Conversely, the results showed that teleworking increased energy consumption regardless of climate zone or building area in the scenarios without a daytime resident. The maximum energy use increase was 4% in Edmonton for the 120 m^2 building model with a full-time teleworker.

To increase the adaptivity of the building to partial occupancy, one possible option is using a smart thermostat and dividing the house into two spaces. This research showed that teleworking in a building with two spaces using a smart thermostat saved energy by 5% maximum compared to a single-space building. In future studies, researchers should explore the effect of office area and its windows orientation on energy consumption and thermal comfort change for two-space buildings. Furthermore, this research assumed that the office hour for the teleworker and occupants with regular jobs (work outside of the home) are the same, but this may not always be the case for all teleworking scenarios. Additionally, this research assumed that the HVAC thermostat worked based on the office whenever this space was occupied, regardless of having a daytime resident in the other space. It can be beneficial if future research considers other possible HVAC control configurations in teleworking scenarios, such as using a variable air volume (VAV) system in a house with more than one thermal zone.

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References

ANSI/ASHRAE (2019). Standard 62.2-2019. Ventilation and Acceptable Indoor Air Quality in Residential Buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Cetin, K. S. and M. H. Fathollahzadeh and N. Kunwar and H. Do and P. C. Tabares-Velasco (2019). Development and validation of an HVAC on/off controller in EnergyPlus for energy simulation of residential and small commercial buildings. *Energy and Buildings 183*, 467-83.

DOE (2020). EnergyPlus™. The U.S. Department of Energy's (DOE) Building Technologies Office. Available at https://energyplus.net/downloads.

Jazaeri, J. and R. L. Gordon and T. Alpcan (2019). Influence of building envelopes, climates, and occupancy patterns on residential HVAC demand. *Journal of Building Engineering 22*, 33-47.

Larson, W. and W. Zhao (2017). Telework: Urban form, energy consumption, and greenhouse gas implications. *Economic Inquiry 55*, 714-735.

Matthews, H. S. and E. Williams (2005). Telework adoption and energy use in building and transport sectors in the United States and Japan. *Journal of infrastructure systems 11*, 21-30.

Nakanishi, H. (2015). Does telework really save energy? *International Management Review 11*, 89-97.

Natural Resources Canada (NRCan) (2015). Survey of Household Energy Use (SHEU-2015) Data Tables – detailed statistical report. https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/sheu/2015/tables.cfm.

Natural Resources Canada (NRCan) (2017). National Energy Code of Canada for Buildings (NECB). Canadian Commission on Building and Fire Codes and National Research Council of Canada.

Natural Resources Canada (NRCan) (2021). Total End-Use Sector - Energy Use Analysis. https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=AN&sector=aaa&juris=ca&rn=1&page=0.

O'Brien, W. and F. Y. Aliabadi (2020). Does telecommuting save energy? A critical review of quantitative studies and their research methods. *Energy and Buildings 225*, 110298.

Roth, K. W., and Rhodes, T., and Ponoum, R. (2008). The energy and greenhouse gas emission impacts of telecommuting in the US. *Proceedings from 2008 IEEE International Symposium on Electronics and the Environment*. San Francisco (USA), 19-22 May 2008.

Röder, D. and K. Nagel (2014). Integrated analysis of commuters' energy consumption. *Procedia Computer Science 32*, 699-706.

Sun Microsystems (2009). Suns Open Work: Energy Measurement Project, A Study of Energy Consumption and Savings White Paper. Retrieved from http://www.smart2020.org/_assets/images/Open_Work_Energy_WP_02-25-09.pdf.