An overview of research projects investigating energy consumption in Multi-Unit Residential Buildings in Toronto

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Abstract

High-rise multi-unit residential buildings (MURBs) constructed in the 1960s and 70s are a prominent form of housing in Toronto; comprising over 50% of the City's residential stock. The majority of MURBs have become problem 'hot-spots' due to aging structures, poor maintenance and inefficient energy use. Studies indicate that MURBs are responsible for emitting over 2.6M tonnes of eCO_2 annually. In 2004, Toronto's Tower Renewal Program was launched to address concerns surrounding MURBs, becoming a municipal initiative in 2008 bridging between various interested parties. This includes a team at Ryerson University, investigating MURBs from an energy-efficiency standpoint. This contribution illustrates the diverse nature of studies undertaken at Ryerson between 2010 and 2015 under the Tower Renewal Program, to understand various facets of energy use in Toronto MURBs.

Studies undertaken are divided into two typologies. The first is aimed at understanding reasons underlying poor performance in MURBs. This includes conducting energy, water and solid waste benchmarking of up to 120 MURBs, and survey-based studies documenting tenants' self-reported behaviors. Finally an ANN model was developed to predict future energy use.

The second typology of studies tests proposed solutions to achieve energy reductions. One proposition simulated building envelope retrofits to meet OBC 2012. A comparison between pre-and post-retrofit standards showed up to 40% reductions in energy use. Finally, as part of a tenant engagement program, an Internet-Of-Things platform was developed and tested to provide visual feedback to tenants about their energy use. Results showed that the program instigated an annual reduction by up to 14.5%.

Introduction

Toronto, the capital of Ontario, is the most heavily populated city in Canada. Approximately a third of the population lives in Multi-Unit Residential Buildings (MURBs), one of the most prominent forms of housing in the City of Toronto. The City of Toronto houses nearly 1,892 MURBs; which is the second highest number of MURBs in North America (City of Toronto, 2016), and comprises over 50% of the city's total residential building stock (Touchie et al., 2013). Most MURBs were constructed between 1945-1980 as part of the rapid urbanization that occurred during the post-war period. At the time, concrete MURBs were considered state-of-the art in modernist design and construction; and considered a trademark of the modernist lifestyle sought by mid-income families; rendering life in MURBs a popular housing choice for mid-income families (United Way Toronto, 2011).

Several decades later, aging MURBs have become problem hot-spots in the city. Most MURBs have severely degraded due to a lack of maintenance (United Way Toronto, 2011). Most rental MURBs are located in neighbourhoods that are isolated from key city infrastructure services (United Way Toronto, 2011); meaning that there are serious securities concerns within these neighbourhoods. As MURBs were constructed in an era during which energy-efficiency was less of a grave concern as it has increasingly become, many of the building features (e.g. concrete frames, non-operational building envelopes and aging appliances) perform poorly. This coupled with little maintenance and/or retrofitting procedures, means that most of the buildings perform poorly from an energy-efficiency perspective (City of Toronto, 2016). Correspondingly, it has been found that MURBs are responsible for emitting over 2.6M tonnes of eCO_2 annually (Touchie et al., 2014).

All of these features compounded have meant that the quality of life in MURBs has significantly deteriorated over time, and MURBs have transformed from a popular housing type for mid-income owners to become an affordable housing option for lower income tenants. Today, about 800 of Toronto's MURBs have privately owned rental properties. With little or no understanding of individual energy use, most tenants are reluctant to invest in energy-efficient appliances or improvements. From a building owner's perspective, there is similarly little motivation to invest in improving or retrofitting building features. Raising the rent is seen as a faster and easier response to rising energy costs than retrofitting; as payback of the latter is much slower (City of Toronto, 2016b; Counihan & Nemtzow, 1980). For some, demolishing these concrete towers and replacing them with newer developments with more energy-efficient features is a favourable solution to eradicate these problem hotspots. However, instigating retrofitting measures in MURBs, which provide affordable housing and offer large-size units for tenants, would improve quality of available housing. Similarly, revitalizing the neighbourhoods in which these MURBs are located promises greater benefit for the communities that reside within them, by ensuring occupants' health and comfort (ERA Group, 2011).

Toronto’s Tower Renewal Program and Ryerson University’s involvement

Inspired by similar community revitalization initiatives undertaken in Amsterdam and Berlin (Mehar, 2011), Toronto’s Tower Renewal Program was launched in 2004 to address concerns surrounding MURBs. The program was adopted by the City of Toronto, making it a municipal initiative in late 2008. The overarching aims of this multi-component program include renewal of the aging physical features and structures of the buildings, and renewal of the urban communities and neighourhoods within which these MURBs are located; by making social improvements through job creation also toward increasing levels of safety in these neighbourhoods (City of Toronto, 2016b). A number of interested parties converge under the Tower Renewal umbrella, including Canada Mortgage Housing Corporation (CMHC), Ontario Ministry of Municipal Affairs and Housing (MAH), City of Toronto government agencies (e.g. TCHC), universities (e.g. University of Toronto and Ryerson University) and NGOs (e.g. Toronto Atmospheric Fund (TAF)). Seeing as Toronto has the second highest high-rise building density in North America, the Tower Renewal Program serves as an enormous opportunity to contribute toward sustainable development across all three of its spheres; by creating stronger communities, increasing local economic activity and improving environmental quality.

It is stated in the Toronto Renewal Implementation Book that if *“water and energy use and their associated greenhouse gas emissions can be drastically reduced; the production of renewable energy can be achieved; social networks, a sense of safety and the ease of traveling in the community can be considerably strengthened; and significant economic growth through job and local business creation realized”* (Pennachetti, 2010). From an energy and resource-efficiency vantage there is enormous room for improvement; the City envisages that savings in MURBs of up to 50% in electricity use can potentially be made and 70% savings in natural gas use (City of Toronto, 2016c). These would equate to 5% reduction of municipal energy consumption (City of Toronto, 2016c), and contribute to the Ontario government’s plan to reduce carbon emissions from buildings by 15% in the Province by 2030; reaching zero emissions by 2050 (The Globe and Mail, 2016).

Between 2010 and 2015, a team of researchers at Ryerson University’s Faculty of Engineering and Architectural Science (FEAS) has undertaken investigations and piloted studies of diverse natures as part of the energy and resource-use component in Toronto’s MURBs. The purpose of this contribution is to therefore illustrate the diverse nature of studies undertaken at Ryerson University under the Tower Renewal Program, to better understand various facets of resource consumption in Toronto’s MURBs.

Overview of Studies Undertaken

Studies conducted on Toronto MURBs as part of Ryerson University’s contribution to the Tower Renewal Program are divided into two broad typologies. The first is aimed at understanding reasons underlying poor performance in MURBs. The second typology of studies tests proposed solutions to achieve energy reductions. In the forthcoming sub-sections, we outline studies falling under these two research categories.

1. Understanding poor performance in Toronto MURBs.

a) Energy, water and solid waste benchmarking

'Energy benchmarking' refers to the comparison of energy use with energy use in buildings exhibiting similar characteristics (Nikolaou et al., 2011). The purpose of benchmarking energy consumption is to promote efficient use of energy. Knowing that the energy used by a building is excessive is the first step to making positive changes (MacDonald and Livengood, 2000). By developing a benchmarking tool, one can estimate energy consumption of similar buildings and determine if a sample building is more efficient than other similar buildings (Chung, 2011).

With respect to MURBs, one major obstacle is that little is known about the energy intensity of that sector of residential buildings. For policy makers, energy benchmarking in existing high-rise MURBs would provide a realistic goal for setting building energy efficiency standards. There is an urgent need to benchmark a significant number of high-rise MURBs, to serve as a representative sample. Robust and accurate models are essential during the baseline process, and also to develop effective policies. These same benchmarking methods can then be used in future to determine whether buildings meet regulatory and baseline certification requirements.

To address this gap in the knowledge, an energy benchmark was developed by Huang (2012) to understand current energy use in 46 high-rise MURBs in Toronto. Of the 46 participating MURBs, 45 were gas heated and only one was heated by electricity. The number of floors of the buildings surveyed ranged from 7-24. The gross floor area of MURBs in this study ranged from 9,240m^2 to 34,850m^2. The number of residential units ranged from 128 and 439, with a mean of 252 units. The mean floor area per unit (including common areas) was between 55m^2 and 127m^2. Previous research shows that occupancy type has great influence on energy use (Enermodal Engineering Limited 2001), but unfortunately, occupancy type was not specified in the data collected from this study. Nevertheless, it is possible to infer to some degree occupancy type based on average unit size. Units less than 60m^2 were likely occupied by single persons or small families, whereas buildings with a mean greater than 120m^2 most likely accommodated for larger families.

Benchmarking was compiled by weather normalized annual energy consumption (NAC) of each MURB, which was calculated using PRISM to the 30-year typical weather of Toronto from January 1, 1981 to December 31, 2010 (Fels, 1996). The GHG emissions benchmarking was developed accordingly. To understand what factors influence overall energy consumption of the MURBs, the relationship between NACs and building characteristics such as vintage, gross floor area and occupancy were examined.

Results of this study are compiled and summarized in Figure 1, showing the energy benchmark with estimated end-uses for 46 high-rise MURBs in Toronto. For total energy consumption, building 3902, the electric-heated building showed much higher energy efficiency than gas-heated buildings. The normalized annual energy consumption for the electric-heated building was found to be 174kWh/m^2. For the 45 gas-heated high-rise MURBs, the range of NAC was 242-453kWh/m^2, with a mean of

336Wh/m^2 and standard deviation of 51kWh/m^2. The coefficient of variation, CV, of the sample was 15.1%.

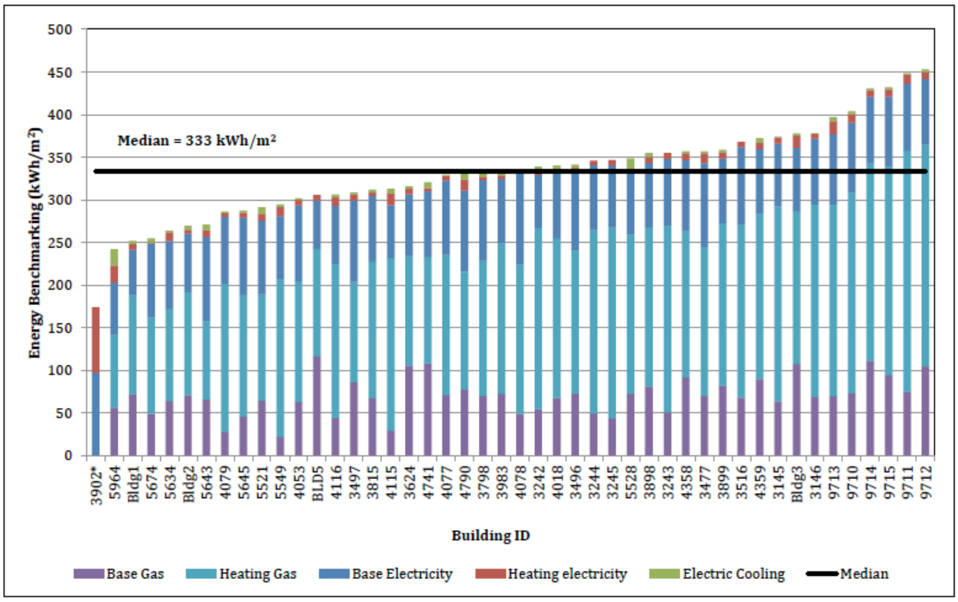

Figure 1: Energy benchmarks of 46 high-rise MURBs in Toronto.

Statistics for benchmarking results are summarized in Table 1. The result shows that the variations of overall energy consumption come mainly from gas consumption. The variation for electricity is relatively small. The CV for total electricity consumption and base electricity consumption are 14.2% and 12.7% respectively. This shows that the electricity consumption is comparable among these MURBs. On the other hand, heating-related electricity and cooling-related electricity showed large variations with CV 49.9% and 82.5%. This part of energy use is most likely to be caused by different and unpredictable behavior of tenants in each MURB. The highest electric demand, 20.1Wh/m^2, is identified in building 5964 (see Figure 1 above). This building was also found to be the most energy efficient building on total gas consumption and overall energy consumption. The gas heating for building 5964 was only 85kWh/m^2, only half of the average. The gas heating is used for central space heating. The high electric heating demand can be explained by the insufficient heating provided by the central space heating, and so tenants used other devices to improve comfort. Even so, the energy consumption for space heating purposes is combined gas and electricity consumption, at 105kWh/m^2; still much lower than the mean gas heating consumption.

Table 1: Summary of energy benchmarks of 45 gas-heated high-rise MURBs in Toronto.

		Total energy consumption (kWh/m^2)			
Normalized annual consumption - overall	Lowest consumption	242			
	Highest consumption	453			
	Mean	336			
	Standard deviation	51			
	CV (%)	15.1			
		Base electricity (kWh/m^2)	**Heating-related electric (kWh/m^2)**	**Cooling-related electric (kWh/m^2)***	**Total electricity (kWh/m^2)**
Normalized annual electricity consumption	Lowest consumption	53.2	0.8	0.9	63.3
	Highest consumption	106.0	20.1	19.2	114.7
	Mean	79.3	7.5	4.1	90.3
	Standard deviation	11.2	3.7	3.3	11.5
	CV (%)	14.2	49.9	82.5	12.7
		Base gas (kWh/m^2)	**Heating-related gas (kWh/m^2)**		**Total gas (kWh/m^2)**
Normalized annual gas consumption	Lowest consumption	21.9	85.0		141
	Highest consumption	116.5	283.2		365
	Mean	70.2	175.7		246
	Standard deviation	22.0	46.5		52
	CV (%)	31.4	26.5		21.0

In a later expansion of the afore-described study, energy benchmarking of 120 rental MURBs in Toronto was conducted. Water and solid waste benchmarking of these MURBs were also performed. Following a similar principle to energy benchmarking, water benchmarking serves as an effective instrument for water conservation policy-making; to set proper water consumption reduction targets for MURBs. Solid waste benchmarking is also a necessary step to improve existing waste management systems, and to reduce the amount of waste being sent to landfills. This is important based on results published by Statistics Canada (2012), which indicated that the amount of waste generated by the residential sector in Canada is the third largest compared to other sectors (Statistics Canada, 2012).

To collect the data required for energy benchmarking, a survey was developed; requesting 2-5 years of monthly utility bills (gas, electricity, water consumption and waste generation), buildings' characteristics (size, age, number, type of units and number of floors), occupancy type and occupancy rate.

Energy consumption analysis was weather normalized using PRISM software, similar to the method used by Huang (2012), to provide a weather-adjusted Normalized Annual Consumption (NAC) index along with best reference temperature for the studied buildings. In this regression model NAC is the dependent variable while HDD/CDD is the independent variable. The degree to which one variable appears to explain the behavior of another variable has been studied by using the coefficient of correlation, R^2. The range of R^2 varies from 0 to 1, in which 0 shows that two variables have no relationships and 1 indicates the perfect relationship between two variables. It had been identified that the most reliable NAC can be achieved when the R^2 is higher than 0.7 and CV (measuring the scatterings of probability distributions) is less than 7% (Fels et al., 1995).

Water consumption analysis and solid waste generation analysis were performed by calculating annual consumption, calculating greenhouse gas emissions (GHG) associated with water use and solid waste disposal for MURBs and applying statistical correlation R^2 procedures similar to that described for energy (to develop water performance indicators and waste generation indicators).

Table 2 summarizes the relationships between each of the consumption variables (energy, gas, electricity, water consumption and solid waste generation) and key building characteristics. The strongest statistical relationships are highlighted in grey. Building size was found to have the strongest relationship with all consumption variables, with the exception of solid waste generation. On the other hand, the number of units in the building was found to have the strongest relationship with annual solid waste generation, albeit a weak correlation.

Table 2: Results of regression analysis of consumption variables and key building characteristics.

	R^2									
	Annual Energy Consumption		**Total Annual Gas Consumption**		**Total Electricity Consumption**		**Annual Water Consumption**		**Annual Solid Waste Generation**	
	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	m^3	m^3/m^2	yd^3	yd^3/m^2
Age	0.02	0.07	0.07	**0.26**	0.00	0.09	0.02	0.00	0.02	0.05
Building size (m^2)	**0.81**	0.00	**0.69**	0.00	**0.74**	0.00	**0.66**	0.00	0.15	0.14
No. of floors	**0.54**	0.00	**0.51**	0.01	**0.50**	0.00	**0.33**	0.00	0.12	0.05
No. of units	**0.51**	0.01	**0.43**	0.02	**0.57**	0.00	**0.37**	0.01	**0.22**	0.04
Capita	**0.73**	0.00	**0.65**	0.00	**0.61**	0.00	**0.66**	0.02	0.13	0.06
Capita/m^2	0.08	0.00	0.05	0.00	0.14	0.00	0.01	0.13	0.01	0.09
Capita/unit	0.01	0.00	0.02	0.00	0.00	0.00	0.06	0.10	0.04	0.00
CDD	0.18	0.00	0.02	0.00	-	-	0.02	0.00	-	-
HDD	0.01	0.01	0.02	0.00	-	-	0.02	0.00	-	-

b) Survey-based studies of tenants' self-reported behaviors.

This section describes studies that were conducted under the rationale that, as a prerequisite to achieving significant reductions in energy consumption, it is important to first understand and evaluate occupants' household energy use and behaviors. This typology of study departs from the premise *that "buildings don't use energy, people do,"* (Janda, 2012), therefore relying on surveys of household energy use. Occupants are requested to provide detailed information on household characteristics (demographics, age, gender, income, etc.) as well as types of appliances owned, numbers of appliances owned and duration of use (e.g. SHEU 2007 in (Natural Resources Canada, 2010)).

There is a limited amount of research done on occupants' household energy use in Canadian MURBs. Most research on MURBs focus on the energy intensity of the entire building quantitatively. There is also a lack of information specifically related to high-rise MURBs at an occupant level. To address this gap, one study conducted at Ryerson (Roque, 2012) investigating occupants' household energy use in a Toronto MURB, evaluated the impact of various factors on household energy consumption in one Toronto rental high-rise MURB situated in downtown Toronto. Monthly profiles of various factors, and their impact on household energy consumption were developed using an artificial neural network (ANN) model.

Artificial neural network modeling is able to discover internal relationships between data. It is able to classify nonlinear relationships with incomplete and small datasets. Because of this, ANN has become a huge interest in many fields and has matured over the past 40 years (Dayhoff and DeLeo, 2001). ANN is used for many applications, including national green energy use analysis (Ermis et al., 2007), public awareness campaign assessments (Mohamed and Alajmi, 2010), depression symptom analysis (Nair et al., 1999), perceptions of building quality (Rebano-Edwards, 2007), energy dependency projections (Sozen, 2009) amongst others. Recently, ANN has been used to predict energy consumption and distinguish relationships based on household energy use behaviour data. For example, Aydinalp et al. (2002) and (2008) use national household energy use survey data to discover relationships between the data. The study described here uses the same methodology as Aydinalp et al. (2003) to develop a similar ANN model.

The MURB that is the focus of (Roque, 2012) is owned and operated by a not-for-profit organization that provides affordable housing for primary single persons of modest incomes. The MURB recently underwent sustainable retrofits such as geothermal and solar thermal domestic hot water heating, sub-metering, etc. the MURB displays similar characteristics to a majority of Toronto MURBs; namely housing low-income households, and classification as a high density residential structure built between 1945 and 1984. Tenants do not pay for their energy consumption, which is included in the monthly rent. The MURB consists of 136 sub-metered units that track electrical energy consumption data per apartment unit.

A survey tool, consisting of 51 questions, was developed to collect information regarding household characteristics, electrical devices and appliances owned and used, heating and cooling, lighting, cooking activities and tenants' energy behaviors. The survey was distributed in the Toronto MURB between April 16th and May 4th 2012, and retained 49 usable responses.

The ANN model was created by using the Alyuda NeuroIntelligence Version 2.2 software and using a similar methodology as Aydinalp et al. (2003). In order to create the model, three sets of data were needed – survey data, weather data and energy consumption. Figure 2 below shows a flowchart of the methodology for the development of the neural network model. The result of the model is its ability to predict an occupant's energy consumption based on weather conditions and various factors from the survey. The output of the model has the ability to give an occupant's energy consumption (kWh) on a monthly basis.

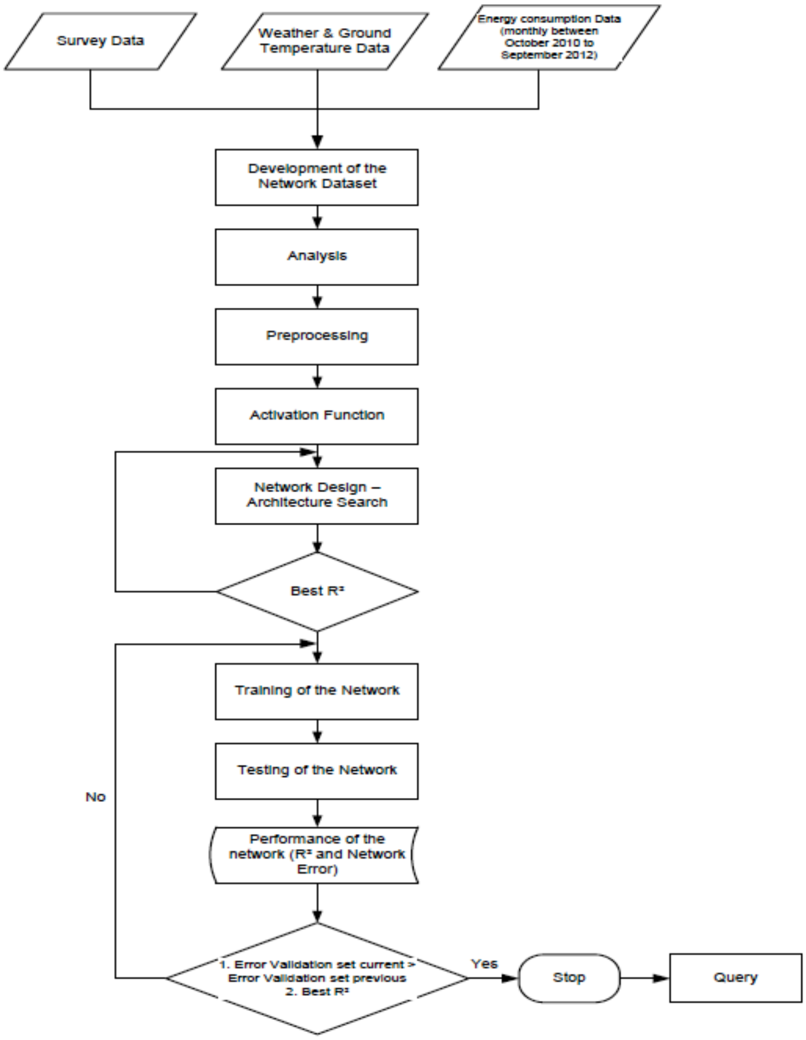

Figure 2: Flowchart of the methodology for the development of the ANN model.

Using a similar methodology as Aydinalp et al. (2003), an ANN model was created using a Quick Propogation training algorithm with 151 iterations. The dataset was divided into three sets – training, validation and testing. The training set creates the ANN model. The validation sets checks the model and the testing dataset fine-tunes and strengthens the model. The R^2 value was used to determine the best network/model. In each dataset, the R^2 was found to be 0.942 for validation dataset and 0.937 for the testing dataset.

General findings of the survey, regarding ownership of household appliances, are shown in Figure 3. The majority of survey respondents own a television, phone charger/lamp/light fixture, radio/stereo, DVD player and computer. Key results from the ANN model developed indicate that overall, males consumed slightly more energy per month than females. Highest income households consumed less than other income groups did, and units oriented in the Eastern direction consumed more energy than Western-oriented units. During the winter months (December to February), occupants who had grown up in Canada consumed 12.5% more energy than those from other geographical categories. On the other hand, occupants who had grown up in South and Central American consumed 21.6% less during winter months. Occupants who spent between 9 to 13 hours in their unit consumed 2.7% less energy compared to other durations of occupancy.

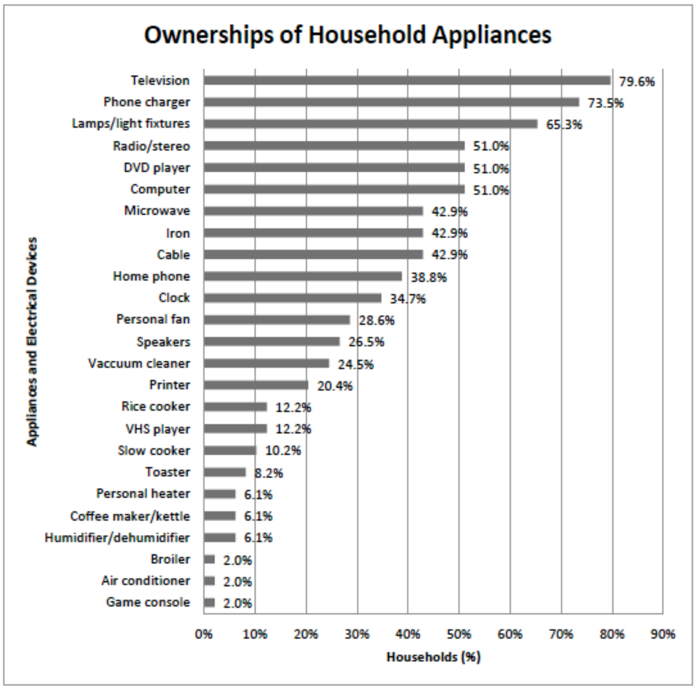

Figure 3: Ownership of appliances and electrical devices in the surveyed households.

In a subsequent survey-based study on the same Toronto MURB, the work of Mohazabieh (2014) aimed at understanding whether a significant relationship could be ascertained between occupants' environmental attitudes and their energy consumption. Previous research in this area (e.g. Thompson and Barton, 1994; Stern et al., 1995 and Poortinga et al., 2004) indicated that positive environmental attitudes do have a substantial effect on pro-environmental behaviors.

To measure tenants' environmental attitudes, the New Environmental Paradigm (NEP) scale (Dunlap et al., 2000) was used. The NEP scale consisted of fifteen Likert-scale statements that could be compounded on a single scale to demonstrate respondents' attitudes. The scale was distributed to 50 participating tenants in the Toronto MURB. Returned responses were categorized as follows:

-Pro-ecological attitudes (scores in the range of 59-75).
- Mid-ecological attitudes (scores in the range of 40-58).
- Anti-ecological attitudes (scores in the range of 15-39).

Historical energy consumption data, collected between October 1st 2010 to December 31st 2013 was weather normalized using PRISM software (Fels, 1996). Subsequently, Pearson's correlations were performed using IBM SPSS software to find whether a linear relationship between attitude data collected and energy consumption could be found at the following intervals:

- Before survey implementation (2011-2012).
- After survey implementation (2012-2013).
- Whole survey implementation (2011-2013).

Results from this test are summarized in Table 3, and significant correlations are highlighted. Significant moderate negative correlations were found between the two variables for the 'after survey' (2012-2013) period and the whole survey duration

(2011-2013). This means that, as occupants' attitude scores increase, their energy consumption decreases.

Table 3: Results of correlation analysis between normalized annual consumption and attitude scores from the NEP survey.

	Normalized annual consumption (kWh) vs. Environmentally-conscious attitudes		
	Before survey (2011-2012)	After survey (2012-2013)	Whole survey duration (2011-2013)
Pearson Correlation (r)	-0.256	**-0.36***	**-0.33***
Sig. (2-tailed) (ρ)	0.073	**0.011***	**0.019***

*Correlation is significant at 0.05 level (2-tailed).

Finally, the implementation of the survey informed about Ryerson's energy efficiency study and may have influenced the tenant's energy consumption. The potential impact of survey implementation was calculated using two methods. The first method used was a comparison of actual energy consumption before and after implementation of the survey. Results of this method indicated that actual energy consumption dropped 8.3% after the survey. The second method created an ANN model using energy consumption data prior to the survey and forecasted the energy consumption after the survey (Before Survey model). Results of this method are shown in Table 4. The results indicate that the prediction from the Before Survey model overestimated compared to the actual energy consumption. This suggests that the respondents consumed less after the implementation of the survey. It can be inferred that by using the Before Survey model, the survey may have had some influence in decreasing occupant's energy consumption by 6%. (The Before Survey ANN model was used to project the same group of occupants' energy demand based on the actual weather conditions after the survey as if there was no survey implemented. In other words, the difference between Before Survey ANN prediction and actual consumption for the after survey (AS) period could be considered as the impact attributed to the introduction of the survey and related tenant engagement activities).

Table 4: Showing difference between prediction from BS Model to Actual Energy Consumption – May to September 2012.

	Prediction from BS Model	**Actual Energy Consumption**	**Difference (Predicted-Actual)**	**Percent Difference**
Total Energy Consumption (kWh)	32329	30299	+2030	+6.3%

2. Proposed solutions to achieve energy reductions

In this section, studies proposing solutions to achieve reductions in energy consumption and improve overall performance are presented. In section 2a, one study exploring the impact of conducting building envelope retrofits on a MURB in Toronto to reach Ontario Building Code 2012 (OBC, 2012) standards is discussed. In Section 2b, an energy feedback research platform designed and implemented in a rental MURB to provide tenants with feedback on their energy use, as part of a tenant engagement program is demonstrated.

a) Building envelope retrofits

It has been identified in previous research that one reason for poor energy performance in MURBs is that some of their physical components reach the end of their lifecycle, while others are in need of major restoration (Kesik and Saleff, 2009). A range of studies conducted (e.g. CMHC, 1990; Genge and Rousseau, 1996; Kesik and Saleff, 2009) agree that numerous deficiencies can be found in MURB building envelopes, and that upgrades are needed to make improvements in insulation, cladding, windows, balconies, exposed structural elements and at the interfaces where two components of the building envelope meet. Building envelope retrofitting is a top priority for postwar MURBs, to address existing problems, preserve a valuable building stock for tenants and improve energy efficiency.

However, prior to beginning costly retrofitting projects, it is essential to evaluate the savings that can be instigated from retrofitting measures. Particularly, thermal resistance value of retrofit projects must be carefully evaluated before application. While increasing RSI values enhance energy conservation, beyond a certain thickness insulation does not have a significant impact on energy savings. The same also applies to airtightness values. Analyzing the impact of increasing the thermal resistance and airtightness on the building envelope can help to identify the optimal upgrade values. Since standards and codes imply the minimum values for building envelope components for new constructions, the research described in Damyar (2014) aims to investigate optimal RSI and airtightness values for a 20-storey postwar MURB in Toronto, up to Ontario Building Code 2012 (SB-10) standards. The research also aims to evaluate how the impact of building envelope retrofits on energy use can be increased and optimized.

Four Building Envelope Retrofit Measures (BERMs 1-4) were proposed; (1) building envelope upgrades based on OBC 2012 (SB-10) standards (BERM 1), (2) incremental upgrades of building envelope components (RSI value) (BERM 2), (3) airtightness upgrades (BERM 3) and (4) combined comprehensive building envelope retrofit and airtightness upgrades (BERM 4).

To understand the annual consumption of the MURB, it was necessary to model the MURB in an energy simulation tool, and use this simulation to represent the baseline energy consumption of the building. Each upgrade could then also be simulated in the program, allowing us to quantify the impact of each BERM and comparison of the results instigated from each retrofitting scenario. The simulation tool selected for this purpose was The Quick Energy Simulation Tool (eQUEST), developed by the U.S. Department of Energy (DOE).

A base case energy model of the building was created in eQUEST using the information presented in the Tower Renewal Guideline Report and the model was calibrated so that gas and electricity use intensity of the model was close to previously reported values in Kesik and Saleff's (2009) study. Four other models were created, each changing one of the criteria based on BERMs 1-4 identified earlier to evaluate its contribution on energy intensity of the building. After evaluation of BERMs based on energy-efficiency measures, 4 major building envelope retrofit strategies (roof, exterior wall and balconies, windows and ground floor slab) (BERMs 5-8) were compared based on their energy-efficiency measure (BERM 8 is a comprehensive building envelope retrofit).

Results are illustrated Figure 4; showing the baseline energy intensity and the difference in energy intensity between the baseline and each of the retrofit cases. Percentage values indicate the improvement levels from the baseline. Results indicate that most of the energy savings can be attributed to a reduction in natural gas space heating. Electricity savings are negligible in comparison to natural gas since their impact on energy intensity was found to be less than 0.4%.

BERM 8, the comprehensive building envelope retrofit was found to have the most energy reduction benefit of 44.3%, followed by BERM 3 with 27% reduction. The impact of window and door upgrades (BERM 2) follows (BERM 3) with a 9.4% reduction. The roof upgrade (BERM 1) had the least impact on energy intensity (0.8%) because roof heat losses make up a smaller proportion of the total building heat losses in the base case.

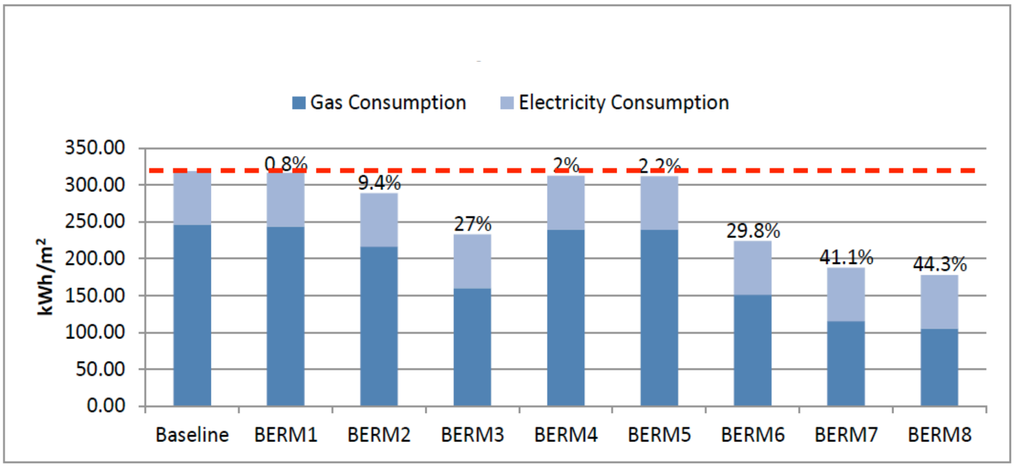

Figure 4: Annual energy consumption intensity analysis of upgrades of building envelope components based on OBC 2012.

b) Energy feedback research platform

The research described in this final study from (Trinh, 2016) is founded from the vantage that providing residential tenants with feedback on their energy use can serve as an effective intervention to instigate energy savings by up to 12% (Erhardt-

Martinez et al. 2010). However, despite the development of many commercial implementations of feedback and a plethora of studies on the efficacy of feedback approaches, researchers (e.g. Erhardt-Martinez et al., 2010; Fischer, 2008; Flemming et al. 2008) have pointed out two key challenges that limit our understanding of how to best design feedback. The first challenge is in the methodological variation of feedback projects with respect to study design, sampling, data-collection and reporting. The second challenge is that there is no consensus on how to best visually design feedback.

A key aim of this study was to demonstrate an Internet of Things (IoT) near real-time feedback platform that could be reconfigured to test a variety of feedback designs. A comprehensive review of the literature on feedback design and feedback intervention programs (Trinh 2016) revealed seven functional requirements are needed to design a sound feedback research platform:

1. It should allow for the implementation of feedback on a multitude of design dimensions such as visual design, frequency and delivery format.
2. It should allow for aggregated and disaggregated feedback data.
3. It should allow for historical and social comparisons to be integrated with feedback.
4. It should support researchers not only by delivering feedback but also standardizing how data is collected and managed.
5. The data collected should not be limited to simple energy measurements, but should be widened to include survey data, thermal comfort data and energy use data.
6. It should allow for data to be collected with a common structure and data format, to afford cross-experiment data analysis.
7. Because the platform is built on open-source technology it should be freely available for others to use and customize.

For the study, the platform was configured as part of a year-long tenant engagement and energy conservation program, asking tenants to save 10% of their annual energy use while testing the effectiveness of real-time feedback and social comparisons. This field study was conducted on the same rental MURB that was the focus of studies described in Section 1(b) located in downtown Toronto. The primary research question for the field study was: Can combining real-time feedback with real-time social comparisons help communities of users reach individual and collective conservation goals?

Due to spatial limitations, it is not possible to discuss details of the system architecture used to design the feedback, but these are detailed in Trinh et al. (2015) and Trinh (2016). To provide visual feedback to tenants, Android Tablets (ASUS MemoPad 7 HD) were given to 24 tenants who agreed to participate in the study, allowing them to view their own energy feedback dashboards using an app that was developed specifically for the study (Figure 6). Two variations of feedback displays were designed in the app. The first was a basic feedback display showing the daily tenants' energy use as well as their energy use over the previous week (Figure 6a). The second variation added social comparisons to the average of the tenant's neighbours (Figure 6b). The app also allowed participants to complete in-situ thermal comfort surveys on a weekly basis. In addition, each suite was filled with the set of components shown in Figure 5.

Figure 5: Rich-picture diagram of feedback hardware installed for each tenant.
From bottom-left counterclockwise: emonTXv3 installed inside fan coil unit to measure power consumption and air temperature output, emonTH to sense ambient room temperature and humidity, a Raspberry pi gateway/hub, emonCMS cloud service, Android tablet with dashboard app. Additionally, but not pictured, were emonTXv3 units to measure suite-level power consumption.

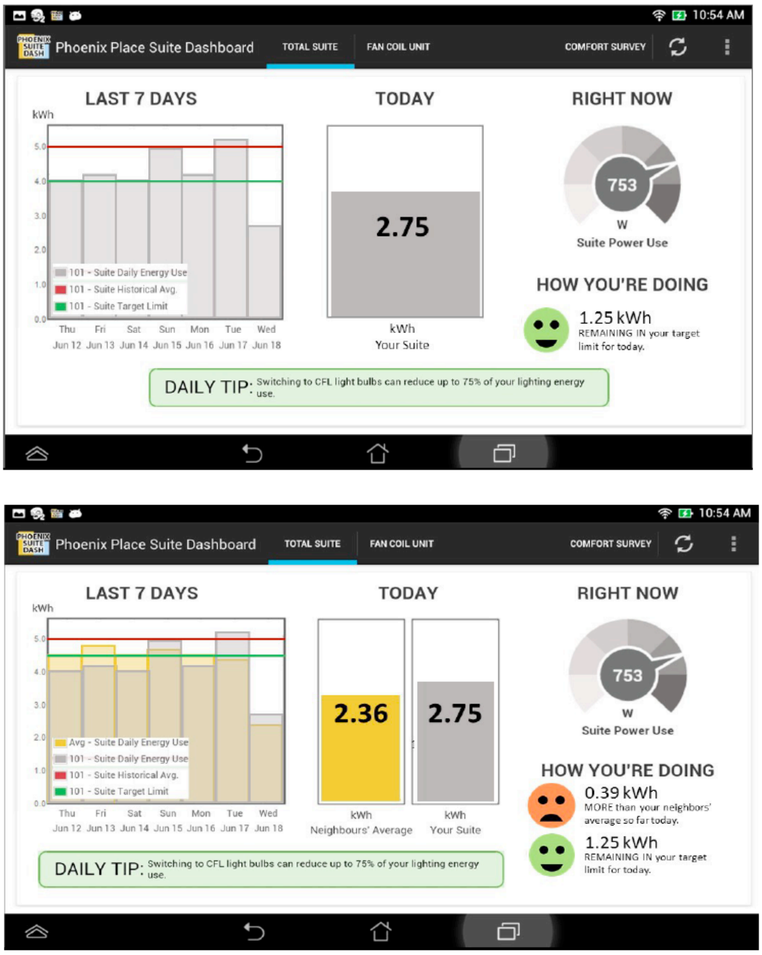

Figure 6: (Above) a) basic feedback display and (below) b) basic feedback display with social comparisons.

The field study used a uni-variate design with feedback type as a between-subjects variable. There were three levels of feedback: no feedback (control), basic feedback (real-time and historical comparisons) and basic feedback + social comparisons. Recruited participants were randomly assigned to receive one of the two feedback conditions. The final counts had 12 participants in each feedback condition and 106 in the control condition.

Results, pointing toward energy savings and the effectiveness of providing tenants with feedback on their energy use, are shown in Figure 7. This shows percentage savings of actual group-aggregated kWh use and weather-normalized group-aggregated kWh use across the three groups of participants. The average annual savings percentage between the two feedback groups was 10.6% compared to an increased use of 2.3% for those outside the study. Similarly for normalized savings percentage, the average for participants receiving feedback was 8.4%, while those outside the study increased their energy use by 2.8%. We can therefore conclude that the tenant energy conservation program and feedback platform was successful in surpassing the 10% energy savings target.

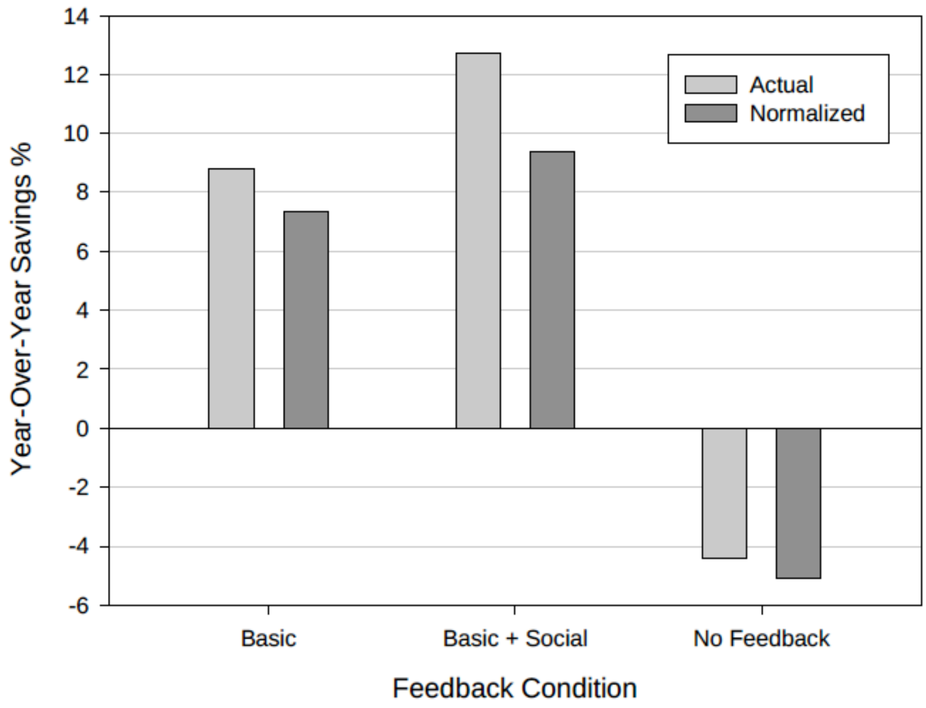

Figure 7: Aggregated year-over-year savings (%).

Conclusion

The purpose of this paper was to provide an overview of the types of research studies conducted at Ryerson University and undertaken within the City of Toronto's Tower Renewal Program. Empirical research described in this paper was performed on rental MURBs, which have been deemed as problem hot-spots in pre-existing literature.

This paper serves as an illustration of the diverse range of research directions that can be pursued, all essentially targeting a unified end-goal; instigating reductions in residential energy-use. It further demonstrates how varying research designs and methodologies can be applied in research focusing on energy-reductions (examples from this paper alone include energy, water and solid waste benchmarking using PRISM, survey-based studies using ANN modeling, simulating building retrofits using building simulation software and finally designing a tenant engagement program and feedback platform).

It is also noticeable that research described here was performed at a broad range of building scales, and targeting alternate dimensions of energy use within buildings. For example, when energy, water and solid waste benchmarking were performed, up to 120 MURBs were observed simultaneously; with each MURB serving as a single unit of analysis in the quantitative study. On the other hand, a more in-depth study was predicated in Damyar's (2010) study; in which only energy flows were studied in only one MURB, and only at the building envelope level, facilitating cross-comparison of multiple retrofit propositions. An even deeper level of granularity was necessary in research aiming to understand the impacts of tenants' individual energy behaviours (e.g. Roque, 2012). When the aim of the research was to instigate change in energy behaviours; the sample consisted of 24 tenants residing in one building; which greatly contrasts with the 120 buildings sampled for Huang's (2012) benchmarking study, where behaviour was largely abstracted and assumed uniform across all tenants. This contrast highlights the multi-faceted nature of energy consumption, and serves as an indication of how energy consumption infiltrates building operation and use across all dimensions.

Moreover, the contrast in research designs pursued opens up a diverse range of avenues in future research that may be pursued towards reducing energy use. For example, it would be interesting, and predictably more fruitful from an energy reduction perspective, to combine multiple methodologies described in this paper (e.g. retrofitting building envelopes coupled with tenant engagement programs and feedback platforms), and to determine whether energy reductions instigated are equally multiplied. Finally, the ability to foster significant and non-negligible reductions in energy consumption using the methodologies described in this paper points toward their applicability in more typical housing types (e.g. high-rise condominiums and single-family housing) offering housing solutions to more representative households (i.e. households consisting of two ore more people) in Canadian cities.

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