# Estimating commercial/institutional building energy consumption and carbon emission trends and measuring stair/elevator usage patterns

by

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# AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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# ABSTRACT

This study identified energy/emission baselines for comparison to the potential savings of new zero carbon buildings. In addition, tenant behavior was studied to see whether the usage of elevators and stairs changed from the initial office buildings to the new zero carbon building. Buildings are one of the largest energy users in many countries. As a result, it is essential to find ways to save energy and reduce emissions from buildings in order to achieve national emission reduction goals. Improvements in energy efficiency and carbon savings have already been demonstrated in building science research. In addition to the technology in the building envelop and heating/cooling systems, the choices made by users are important factors of overall building performance. In this study, one discretionary choice will be examined in detail: will people use a prominent central staircase instead of using the elevators? A certified Zero Carbon Design Office Building in Waterloo will be examined as a case study to determine whether moving into a high-performance building is associated with a corresponding change in pro-environment behavior, namely, the use of central stairs instead of the central elevators.

Tenants of this new building include local businesses, a cleantech incubator, an environmental nonprofit organization and university groups. A five-year research plan was made for the case study and the building has served as a “living lab” for researchers to study the energy/emission performance improvements as well as behavior changes. This study has two main parts. First, the energy/emission baselines for the tenants were calculated based on the previous years’ data from the tenants’ old buildings. The main purpose of establishing the baselines was to identify the potential energy/emission savings. Second, human behavior changes were studied through the observation of tenant elevator and stair usage ratios. In previous literature, it was indicated that the preference of sustainable behavior – using stairs instead of elevators in office buildings – was complicated and affected by multiple factors such as building design, demographics, and interventions (engagement workshops/activities). In this study, the relationships between the use of elevator/stairs and some of the effective factors were identified, and a stair/elevator usage ratio was calculated. Finally, the energy consumption of using elevators in the zero carbon building was calculated. The results of this study showed that design influences behavior as a prominent central stairs can increase the proportion of people using stairs by 42%. The combination of net zero carbon building and general interventions (sustainability workshops) to encourage sustainable actions corresponded with increased stair use by 5% compared to pre-occupancy levels. Multiple factors affected people’s stairs choices: people on the second floor used stairs 29% more than those on the third floor; and people took the stairs 16% more often when descending compared to ascending.

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# CHAPTER 1

# Introduction

## 1.1 Definitions of Key Terms

*Building citizens*: Individuals who work in a building, such as operators, managers, employees, etc., or who have agency and responsibility towards the functioning of the building. (Fernandes et al., 2018)

*Chi-square test*: The Pearson's chi-squared test (chi-squared test for short) is used to determine whether the expected frequencies and the observed frequencies in one or more categories are significantly different from each other.

*Doppler Effect*: The change of wavelength or frequency of waves when the source of the wave is moving relative to the observer. The different wavelengths or frequencies can indicate the moving directions of the objects.

*End-use energy*: Energy measured at the final use level. (Sartori & Hestnes, 2007)

*Energy efficiency*: The amount of energy needed to provide certain services or do a certain amount of work.

*Greenhouse gas*: A gas that absorbs infrared radiation and contributes to the greenhouse effect e.g., carbon dioxide and chlorofluorocarbons.

*Indirect emission*: Emissions that are a consequence of the activities within well-defined boundaries of, for instance, a region, an economic sector, a company or process, but which occur outside the specified boundaries. For example, emissions are described as indirect if they relate to the use of heat but physically arise outside the boundaries of the heat user, or if they relate to electricity production but physically arise outside of the boundaries of the power supply sector. (IPCC, 2014a)

*Linear Regression*: Regression is a statistical measurement used to determine the strength of relationships between an independent variable and one or multiple dependent variables. Linear regression allows creating a linear approach to modeling the relationship among the variables.

*One-way ANOVA*: Analysis of variance (ANOVA) is a statistical model used to analyze the differences among group means in a sample. A one-way ANOVA is one of the ANOVA statistical models which is used to analyze whether the means of two or more independent groups are significantly different from each other. Only one independent variable exists in the one-way ANOVA test.

*Primary energy*: Energy measured at the natural resource level. It is the sum of all energy used to produce the end-use energy, including extraction, transformation and distribution losses. (Sartori & Hestnes, 2007)

*Renewable energy*: Energy that is from nature, but will not be depleted or exhausted after using e.g., solar, wind, and hydro energy.

*Secondary energy*: Energy that is generated from primary energy e.g., electricity.

*Two-way ANOVA*: This technique is used to compare means of two or more independent groups which are split among two independent variables. The purposes of the test are to ascertain if the two independent variables have significant effects on the dependent variable, and if there are interactions between the two independent variables on the dependent variable.

## 1.2 Background Information

On December 12, 2015, Canada along with 194 other countries set the ambitious goal of limiting the global temperature rise to under 2 ℃, and to make additional efforts to keep the increase below 1.5 ℃. (Government of Canada, 2016) So far, based on Canada's 2016 Greenhouse Gas Emissions Reference Case, Canada’s greenhouse gas emissions were projected to be 722 Mt CO2 equivalent in 2030, which is still much higher than the national goal (523 Mt). (Government of Canada, 2018a) According to Natural Resources Canada, buildings accounted for 28.3% of the total secondary energy consumption and 22.6% of total Greenhouse Gas (GHG) emissions in Canada in 2015. Thus, improving building energy efficiency as well as switching to low carbon energy sources is important for achieving a significant change towards a more sustainable future.

The zero-carbon building is one of the desired solutions for building developers to realize energy efficiency and emission reduction in the current building market. (Kibert, 2016) One of the main reasons for this is the increasing price of energy. (Environment Canada, 2008) The energy-saving features brought about by these zero-carbon buildings are attractive for the market. Furthermore, the expansion of the population and building floor area has put additional burdens on the energy demands of buildings. The building final energy consumption increased about 5% from 2010 to 2016 while the building floor area increased by 17% over these 7 years. (IEA, 2018) The use of renewable energy and energy efficiency techniques played important roles in slowing down the increase of the energy consumption in buildings. In this case, the zero-carbon building, designed with various energy-saving and carbon-reduction techniques, is needed to reduce the energy demands of buildings as well as emissions.

However, a building with energy-efficient designs alone may not achieve the targeted savings of energy and emissions. People also play important roles in building performance. Previous studies showed that people who exhibited energy-saving behaviors can save up to 43% of energy (electricity) when compared to other people who lived in the same building. (Matthies et al., 2011) On the other hand, a very efficient building may exceed its designed level of energy consumption due to the energy-wasting behaviors of its occupants (e.g. leaving windows open in summer/winter). Therefore, studying people’s behaviors is necessary.

### 1.3 Case Study

In the case study targeted by this research, the zero carbon building, was designed to have net-positive annual operating energy. More than just using less energy, this building can also provide net energy back to the grid. (Cora Group, June 23, 2017) The purposes of this study were to, first, prepare current energy consumption and carbon emission profiles (establish baselines) for tenants and estimate potential energy and carbon savings that can be achieved by this new building; second, study the behavior changes brought about by occupancy in a zero carbon building as indicated by tenants' elevator and stair usage. In terms of setting up the energy and emission baselines of the case study building, tenants' previous energy and carbon profiles were calculated from the energy consumption/carbon emission data of their previous buildings. Then, these data were used to set up the energy and emission baselines of the new building, which could show their potential energy and emission reductions after they moved into the new building. In addition, these values were prepared to be compared to the actual energy and emissions from the operational phase of the building, in order to test if the "net-positive" goal was indeed achieved. For elevator and stair usage, there were three stages of the study: pre-occupancy, post-occupancy, and post-engagement. "Engagement" refers to various activities and workshops in the building that people can attend in order to improve their understanding of sustainability and encourage them to take actions.

For each of the stages, observational data of people using stairs and elevators were collected. For the post-engagement stage, sensor-reported data were available from the four people-counting sensors installed in the building. Observational data went beyond elevator and stair choices by people to include age cohort, gender, direction of movement, grouping behaviors, and floor height in order to analyze the situation more comprehensively. The comparisons happened among each of the three stages in order to see if interventions were strong enough to stimulate changes in people's behaviors. Then, the elevator and stair usage by the people in the building was analyzed and a baseline value of the usage was established. Finally, the energy consumption of using elevators in the building was calculated, which allowed linking human behaviors to building performance. This research was the first step in the ongoing evaluation of this building's operation and performance. Most of the results can serve the needs of future research for the five-year project.

## 1.4 Research Questions

The research questions of my thesis study are: What are the historical trends of building energy/carbon performance? What are the estimated energy/carbon baselines in previous tenants' buildings for comparison to the zero carbon case study building? Does a zero carbon building affect people's behaviors (e.g. elevator and stair usage)? What are the elevator and stair usage baselines in the new building? For this study, both primary data and secondary data were used. The secondary data were comprised mainly of energy/emission data for setting up the baselines, and the primary data were both observational and sensor data that allowed studying stair/elevator usage. Multiple statistical tests were used for data analysis. Discussions related to the main findings and results will be provided.

## 1.5 Conceptual Framework

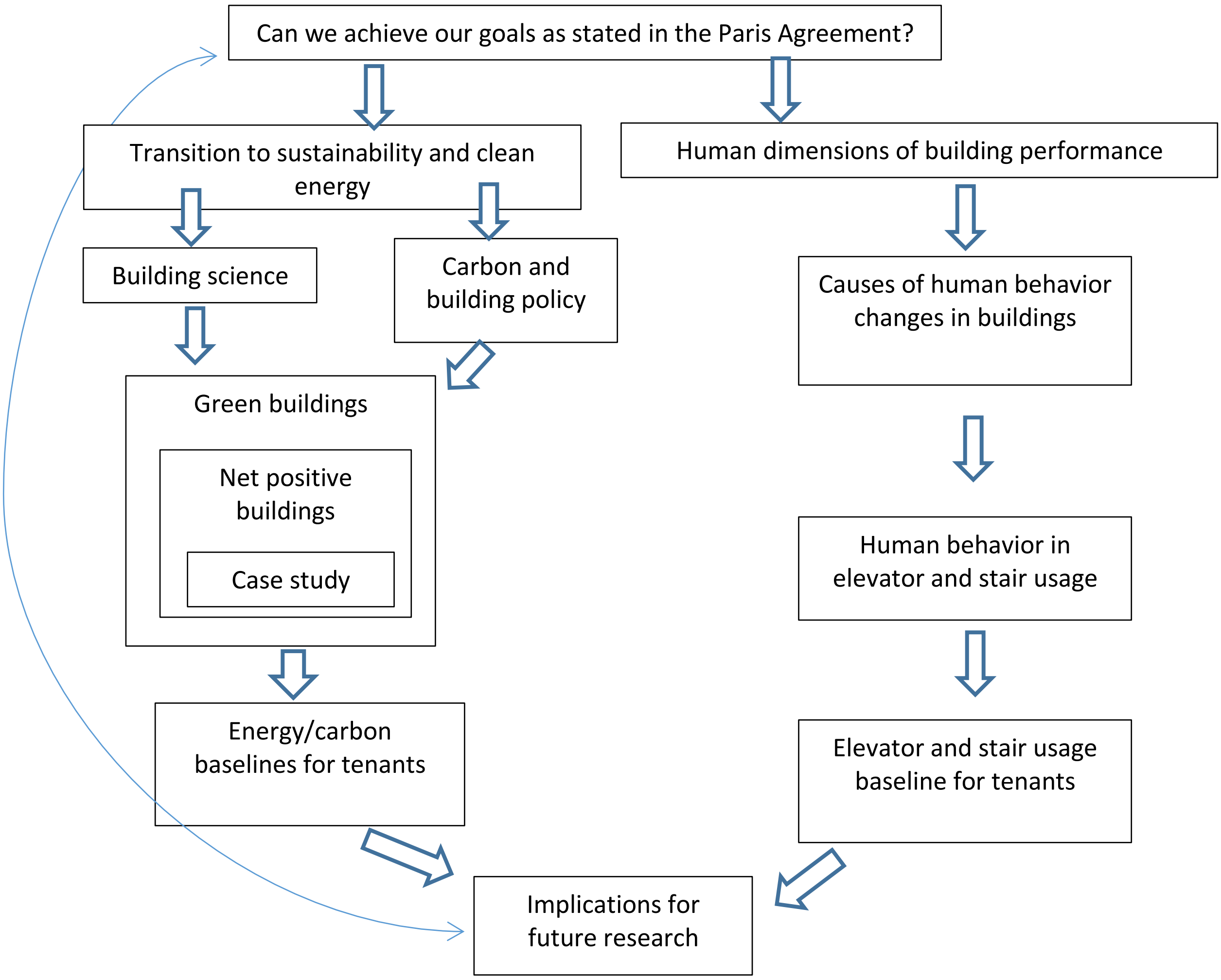


Figure 1.1 Conceptual framework

# CHAPTER 2

# Literature Review

## 2.1 Building Energy and Emission Baselines

### 2.1.1 The Transition Theory in Buildings

The transition theory is widely used in different research fields in order to show the changes of a problem or a phenomenon with respect to the changes of other factors. Caldwell argued that a transition theory is used to show that "past movements and our expectations about future trends rest primarily on a body of observations and explanations". (Caldwell, 1976) Thus, the transition theory teaches us to look at not only the changes but also the trends in these changes, and the both primary data collection (observations) and secondary data collection (literature) are important to study. In 2005, Omran researched the epidemiologic transition by using a theory of the epidemiology of population change. (Omran, 2005) In this study, he also showed that epidemiology transition patterns are closely related to demographic, economic and sociological patterns in many ways, indicating that the transition theory will include not only the targeted object of the research, but also all the related and effective objects. It is closely related to the present study since various demographic data and influential factors will be recorded and analyzed. Similarly, in building industries, research is targeting the future (e.g. goals for 2030), and it is not only our current achievements that are important, but also the realization of the progress and trends. In other words, "how we got to where we are" can be of prime importance in determining our future movements.

A study about sustainability transition by Shaw et al. (2014) showed that in order to achieve environmental goals, people may be required to act more at a local level (e.g. communities) than at the higher levels (provincial, national, international). The research gathered data from 11 communities within British Columbia, Canada, and identified two broad approaches to climate actions. First, it was stated that primarily either a mitigation or adaptation focus would be chosen, with varying levels of integration (or consideration of synergies/tradeoffs) involved; Second, among 11 targeted communities, the 6 regarded as leaders all used a sustainability-focused approach, which “employs different sustainability framings to support climate mitigation and adaptation actions and the unique partnerships and inter-governmental arrangements are required to design and implement these actions.” (Shaw et al., 2014) In other words, the most efficient way to accomplish a transition to sustainability would be the implementation of local actions alongside policy and government support. For example, the development of a net-positive building studied in this research can be regarded as one approach for the local region (Waterloo) in transiting to sustainability with the policies and financial support of the government.

The clean energy transition is another transition process that has been occurring within the building industry. This transition aims at replacing fossil fuel use in buildings with cleaner energy, such as low-carbon electricity. Reported by IEA, fossil fuels account for 36% of the final energy consumption in buildings and generate 2.9 Gt CO2 equivalent in annual emissions. In this case, shifting to low-carbon electricity in buildings can bring considerable improvements in energy and emission performance with advanced energy-efficient technologies. However, the increase in demand of electricity may be limited by the current energy-producing industries. Careful planning in the power sector will be needed in order to achieve a net reduction in emissions. (IEA, 2018)

The evolution of buildings is above all related to the development of technology. One clear example can be seen in the improvements in solar power. Passive designs have led the way to advanced technical systems. Around 500 B.C. in Greece, building houses oriented to the south was the norm (48), and in 400 B.C. solar chimneys were designed for natural ventilation of houses in the Roman Empire. In the year 1760, the first solar collector was built by Horace de Saussure in Switzerland, (49) and after that, solar energy became an ever more common alternative energy source. The first “solar-energy based” building “Solar House #1” was built in the USA at MIT University in 1939. Since then, a series of MIT buildings have been built and the most recent one, Solar house #7, built in 2007, can produce more energy than it uses. However, the evolutionary progress of buildings is not determined only by technology. With advanced building designs, actual building usage is also closely related to building performance, and the detailed effects of how human behaviors actually influence building performance will be discussed later.

### 2.1.2 Energy and Carbon Status – Global, National and Provincial Trends

Based on the data provided by the International Energy Agency (IEA), the global primary energy supply increased from 6,101 Mtoe (million tons of oil equivalent) in 1973 to 13,647 Mtoe in 2015. In addition, the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) showed that the total of all anthropogenic GHG emissions has continued increasing from 1970 to 2010, and reached 49± 4.5 Gt CO2 eq/yr. The reasons for these increases were various. Recently, as projected by the IEA based on new energy policies worldwide, the global energy consumption will increase by another 30% from the year 2017 to 2040, and the main driving factors will be the growth of economy, the expansion of population, and the process of urbanization. (IEA, 2017d) Considering the GHG emissions by sources over the past 40 years, industry and fossil fuel combustion accounted for 78% of all GHG emissions (IPCC, 2014b).

Building industries accounted for 6.4% of the total direct anthropogenic GHG emissions and 12% of the total indirect anthropogenic GHG emissions (from electricity and heat production), making them one of the biggest energy consumers and carbon emitters. (IPCC, 2014b) Meanwhile, the numbers have been increasing in recent years. Since 2010, the global building carbon emissions have increased by 1% annually. While the energy intensity in building industries dropped by 1.3% annually from 2010 to 2014, still, with the 3% annual increase rate of building floor area, the energy demand of the building sector continued to show a rising trend. (IEA, 2017b). Furthermore, with the fast development of their economies, the Non-OECD countries tend to have a larger energy demand and faster annual increases in energy demand and carbon emissions than OECD countries. However, no matter who and where we are, in order to achieve the “2 Degree Celsius” target, the average energy consumed by the building sector per person must drop by 10% minimum to less than 4.5 MWh by 2025. (IEA, 2017a)

Reported by IEA in 2015, North America had the highest CO2 emission rate per capita in the world, which was 15.2 tons CO2 per capita. (IEA, 2017c) In North America, the United States and Canada are the two major countries of global energy consumption and CO2 emissions. In the year 2008, the per capita primary energy supply was 8.1 tons of oil equivalent in Canada, which placed it third worldwide, higher than the United States. In the same year, the total CO2 emissions from fossil fuel combustion in Canada was 573 million tons, which was lower than that of the United States and ranked 4th place globally. (Statistics Canada, 2012) Canada is one of the most energy intensive countries in the world, and its building industries also accounted for a significant proportion of the energy and carbon footprint within the county. Natural Resources Canada reported in 2015 that the energy consumption by the residential sector was 1,544 PJ, and the total GHG emissions were 65.4 Mt of CO2e (CO2 equivalent). Meanwhile the total energy used in the commercial and institutional sectors was 1,009.4 PJ, and the total GHG emissions came in at 45.2 Mt of CO2e. Buildings in Ontario accounted for about 40% of provincial energy consumption and 30% of these GHG emissions.

### 2.1.3 Carbon and Building Policy

In the Paris Agreement, Canada committed to reducing GHG emissions by 30% below the 2005 levels by the year 2030. (Government of Canada, 2016) So far, the national goal is set to be 523 Mt CO2 equivalent in 2030, however, a projection showed that based on measurements in September 2017, our current efforts can only achieve a level of 722 Mt CO2 equivalent emissions in 2030, which means there are still further actions to be taken for the national goal. (Government of Canada, 2018a) In 2011, the National Energy Code of Canada for Buildings was released. This code established regulations for minimum building requirements, including lighting, heating, ventilation and air-conditioning systems, service water heating, and electrical power systems and motors. Following that, in the year 2015, more stringent and specific requirements were made by a new version of the national building code in order to improve energy efficiency and reduce carbon emissions in Canada’s new buildings through higher standards. (Natural Resources Canada, 2017a,b)

Ontario also adopted and referenced the National Energy Code for Buildings in its own building code and consequently set its emission reduction goals: reducing from the 1990 emission level by 15% in 2020, 37% in 2030, and 80% in 2050. Ontario has already achieved a 6% reduction from the 1990 level in the year 2014. (Government of Ontario, 2016b) In order to further reduce emissions, in Ontario’s Five-year Climate Change Action Plan, more actions are to be taken in six main industries including transportation, buildings, electricity, agriculture, waste treatment, and others. In building industries, there will be three main thrusts for future actions: generating cleaner power, providing more low-carbon products and services, and improving energy efficiency in existing buildings and new buildings.(Government of Ontario, 2016b) Ontario's long-term infrastructure plan of 2017 mentioned that the infrastructure will be aligned with climate change priorities. In this case, the government will consider taking various approaches in order to reduce the GHG emissions from infrastructure, including improving the life cycle assessment of infrastructure, reducing waste generation, and reducing the carbon footprint of the government. (Government of Ontario, 2017)

On January 1st, 2017, the cap and trade program (cancelled on July 3, 2018) came into effect to fight climate change in Ontario. The "cap and trade" was regarded as a very effective tool for controlling CO2 emissions, because it not only used the cap to limit the total GHG that can be emitted by companies and businesses, but also afforded opportunities to trade the GHG emission credits among companies, ensuring that the price of carbon is determined by the market instead of by the government. On September 22, 2017, Ontario signed the cap and trade linking agreement with Quebec and California, which would become effective on January 1st, 2018. (Government of Ontario, 2016a) In this case, companies and businesses in all three places can trade credits with each other, allowing more flexibility and financial benefits in business operation.

Furthermore, the Pan-Canadian Framework on clean growth and climate change was released in December 2016, proposing that starting from the year 2020, provinces and territories should start adopting a "net zero energy ready" building code and finish the process by 2030. (Government of Canada, 2018a) In addition, this Pan-Canadian Framework also proposed new goals and regulations in other sectors such as "the pan-Canadian approach to pricing carbon pollution", which aimed at improving the current carbon pricing system and ensuring the lowest environmental cost caused by businesses and industries. (Government of Canada, 2018b) These changes in policy can be regarded as an incentive for the development of energy-saving buildings.

Outside of Canada, some other countries have also made the net zero energy building mandatory in their buildings policies. The UK is known as the first country that proposed adopting the NZEB. In 2007, the UK announced in its Energy Efficiency Action Plan that it would "improve the energy performance standards" and "deliver zero-carbon homes by 2016". (DEFRA, 2007) Following that, in 2009, the European Parliament voted that by December 31, 2018, all new buildings in the member states should be built as net zero buildings (or net positive), and percentage targets of the number of net zero buildings in each country should be set. (European Parliament, 2010). In Europe, France also established the target that all buildings should reach “energy-positive” standards by 2020. (European Commission, 2009) Hungary proposed requiring zero emissions from all new buildings by 2020. (Thomsen and Wittchen, 2008) In Asia, “Measures to Develop Green Cities and Buildings” was released on November 5, 2009 in South Korea to further improve the energy and carbon standards in the building industry, mainly for residential buildings. (OECD, 2009) In North America, the California Energy Commission adopted building standards to achieve “zero net energy residential buildings by 2020 and zero net energy commercial buildings by 2030.” (California Energy Commission, 2009) Moreover, the “Final Report of the Massachusetts Zero Energy Buildings Task Force” proposed a target of achieving net zero energy for all residential and commercial buildings by 2030. (Massachusetts Zero Net Energy Buildings Task Force, 2009)

### 2.1.4 Net Zero Energy Building (NZEB) and Positive Energy Building (PEB)

Long before the “energy efficiency” concept even existed, people started building houses to conserve energy. As early as 5,500 BC, people in the region of the Carpathians built partially buried houses in order to maintain a constant indoor temperature and increase living comfort. This is usually considered as the first known case marking the beginning of efficient building evolution. (Folk technique and architecture, 1984) The concept of energy efficiency arose in the beginning of the 20th century and the evolution of buildings experienced four remarkable milestone moments in that century. First, in the year 1939, the MIT Solar House #1 was designed and constructed by H.C. Hottel. This building focused on efficient heating during the wintertime, and was the first to integrate solar collectors and water accumulators into a building’s design. (Spitler, 2006) Second, in 1973, the oil crisis broke out. Due to the consequent energy shortage, energy-saving designs in buildings attracted more interest, which accelerated efficient building evolution. (Ionescu et al., 2015) Then, in 1990, the first passive house “Kranichstein passive house” was built in Darmstadt, Germany. (Grove-Smith, 2009). Following that, in the year 1996, the Passivhaus Institut was founded with an eye toward improving building standards in energy-saving building designs. (Ionescu et al., 2015) Lastly, in 1992, a solar house developed by the Fraunhofer Institute in Freiburg, Germany (Fraunhofer-Gesellschaft, 2009) was the first house that was able to produce more energy than it consumed with its high level of insulation and advanced solar energy technologies. (Stahl et al., 1994)

With the challenge of global climate change and the erratic nature of fossil fuel price, high-performance net zero energy buildings and positive energy buildings are becoming more desirable. (Kibert, 2016) It was suggested by Waldron, Cayuela, and Miller in 2013 that the NZEB and PEB are just two practices under the aegis of regenerative sustainable solutions for environmental problems. Regenerative sustainability has been defined as “a net positive approach to sustainability leading to a mutually beneficial co-evolution of socio-cultural (‘human’) and ecological (‘natural’) systems”, which means that research is geared toward seeking actual benefits through positive actions rather than imposing less harm on the environment. (Waldron et al., 2013) Both the NZEB and the PEB were partially developed from passive sustainable designs and are considered to be modern ways of improving the energy and carbon performance of buildings. Some of these buildings also in fact produce energy by using renewable energy techniques such as solar panels. These two types of buildings have recently attracted ever more attention from researchers due to the change in building policies and government regulations. (Kolokotsa et al., 2011)

As defined by Tortellini and Crawley (2006), the “net zero energy building” does not mean that the building consumes no energy, instead, “net zero” means that the energy production of the building can offset its energy consumption. There are four more detailed definitions given by Tortellini concerning zero-energy buildings. Buildings whose annual energy production equals their energy consumption are defined as Net Zero Energy Building Sites (NetZSEB). Buildings whose annual energy production can cover their primary energy consumption are defined as Net Source Zero Energy Buildings (NetZSEB). Buildings that earn as much money from their exported energy production as their energy consumption plus the service fees are defined as Net Zero Energy Cost Buildings (NZECB). Buildings whose yearly use of renewable energy equals their emissions are defined as Zero Energy Emissions Buildings (NetZEEB). (Torcellini et al., 2006) If we consider the whole life cycle of a building, we can then add a further definition of a life cycle zero energy buildings (LC-ZEB), which would be a building whose energy production covers not only the operational energy consumption but also the embodied energy of the building. (Hernandez & Kenny, 2010).

For a typical NZEB design, factors considered by the developer will include building envelope, ventilation system, heating and cooling (water and air), lighting and appliances, energy production, and the energy management system. (Kapsalaki & Leal, 2011) A good example is the NZEB “Solar Harvest” built by Eric Doub and his company Ecofutures Building in Boulder, Colorado. This house was constructed in 2005 with an area of 426 m2. It has both active and passive solar designs along with very good thermal insulation (Wall U-value = 0.17W/m2K, Ceiling U-value = 0.126W/m2K, double-glazed windows, trees and solar panels for shading) and a natural ventilation system. Underground PVC pipes are used for preheating/precooling of incoming air. The solar thermal flat-plate collectors are used for space and water heating. In addition, all the appliances in the house are powered by electricity produced from the solar panels. The energy management system included various temperature sensors and energy sensors to monitor the data outputs from the building. (Doub, 2009) Another example would be the Rocky Mountain Institute Innovation Center building, which is in fact similar to 90% of the commercial office buildings in the US but is designed to be net-positive energy. This building was built in 2016 and has various innovative features that guarantee the building’s sustainability, such as thermal comfort and passive performance. The building also has solar panels on the roof which can provide approximately 114,000 kWh of electricity annually to support the buildings’ energy consumption. (Rocky Mountain Institute, 2019) A net positive building can be defined as a building that produces more energy than it consumes, which is related to, but performs better than a net zero building. In order to achieve this increased performance, these buildings include various energy-efficient or renewable energy techniques in their designs. Generally, the following techniques will be considered: improving building fabric, improving shading devices, incorporating advanced heating-and-cooling systems, using renewable energy, and using an “intelligent” energy management system. (Kolokotsa et al., 2011)

### 2.1.5 Case Study

This research focuses on a newly built zero carbon building as a case study of a net positive energy building. The building, evolv1, was developed and managed by The Cora Group as a net-positive building in the Waterloo Region, and is recognized as “Canada’s first net zero commercial multi-tenant office building.” (The Cora Group, June 23, 2017) In 2016, the building was selected for participation in the “Zero Carbon Building Pilot Program” held by the Canada Green Building Council along with 15 other elite building projects. The 110,000sf building was designed to produce more energy than it consumes. (Canada Green Building Council (CaGBC), 2019) In order to achieve the required energy and carbon reduction of a net positive building, it incorporates various energy-saving techniques into its design: a LED 0-10V dimmable lighting system with occupancy sensors and daylight harvesting; a 300 ton Geo-exchange / VRF HVAC system within an innovative open well; an ultra-high efficient variable refrigerant flow mechanical system incorporating a heat pump and chilling equipment; a 40,000 liter cistern for rainwater harvesting and storm water management; an exterior solar wall system for fresh air exchange and preheated ventilation; a sophisticated building automation system, including extensive measurement and verification; a solar panel covered parking lot with EV charging stations and priority parking spots; triple glazed windows throughout the entire building in order to improve the use of natural light while raising the insulation level; a three-story green wall to improve the indoor air quality; a highly efficient envelope and ventilation system to meet a defined threshold for thermal energy demand intensity; and other renewable energy systems. Overall, with all the sustainable techniques applied, the building is expected to generate more energy than it consumes with its 700kw photovoltaic array, and to reach the market-leading position for indoor air quality. (The Cora Group, 2019) The Evlov1 building is a LEED Platinum candidate, and by incorporating all of these energy-saving techniques, the building is expected to meet its net-positive promise. (The Cora Group, June 23, 2017)

After the grand opening of the building, additional sensors were installed to monitor the detailed operations. Sensors for the indoor environment quality measured indoor humidity and temperature values. In addition, people counting sensors were placed at entrances, elevators, and stairs to record the overall indoor traffic and human behavior. Monthly “sustainability engagement activities (including workshops)” were arranged by the Manager of the Culture of Sustainability for the tenants to share their sustainable experiences during their working hours within the building. Through these activities, the Sustainable Waterloo Region staff also offered some suggestions on how to work/live in a more sustainable way based on their knowledge of sustainability. This information was imparted in interesting ways, as stated by the manager, “instead of teaching people what to do or trying to educate them, we’d better let them have fun while learning sustainability.” As a living lab, the building is a perfect place for us to test whether a zero carbon office building can bring changes in both energy/emission reductions and people’s living behaviors.

## 2.2 The Elevator and Stair Usage

### 2.2.1 Importance of Human Dimensions of Energy Use in Buildings

In addition to advanced technology and smart building designs, human behavior also contributes to overall building performance. As stated in the literature, “technology investments alone do not necessarily guarantee low or net-zero energy, or higher comfort perception, in buildings”. (D’Oca et al., 2018) In other words, while technology and design investments can *theoretically* guarantee overall building performance (e.g. energy use, emissions, ventilation etc.), the building serves people, and people’s perception of a comfortable working or indoor living environment. A comfortable and healthy indoor environment is essential since people spend more than 90% of their time indoors. (Zhao et al., 2014) Globally, energy consumption to condition the indoor environment consumed over 40% of total energy over the last ten years. (Dounis & Caraiscos, 2009)

In order to render their indoor environment more comfortable and productive, people’s behaviors can be categorized into two types: the first is called “adaptive actions”, meaning that people take certain actions to adapt the indoor environment to their preferences or needs, for example, turning on/off the lights, opening/closing the windows, and turning on/off the fans. The second is called “non-adaptive actions”, which are all the other actions that are not adapted in any way, including operating plug-in devices and movement through the spaces. (Hong et al., 2017) Both categories comprise human interactions with the building, which affect the overall building energy use and modifications in these interactions may result in significant changes.

Studies have shown that in a typical office building, occupants who perform energy-saving behaviors consume 50% less energy than those who do not. (Lin & Hong, 2013) Furthermore, some research has shown that occupants’ behaviors can in fact be regarded as one of the fundamental factors that affects building energy efficiency, and can possibly raise building energy performance as much as innovative technology does.

Ouyang and Hokao studied the potential energy savings that can be achieved by improving occupants' behavior in the urban residential sector of Hangzhou City, China. They examined a sample of 124 households in total, and gathered data on all their electricity consumption in July 2007. Then they gave half of the households "energy-saving education" before July 2008 and gathered data on their electricity consumption for that month. After refining the data for the variation of other factors such as temperature and increasing use of household appliances, energy consumption dropped by approximately 14% among those "educated" households on average. (Ouyang & Hokao, 2009) As well, in year 2017, Zhao et al. showed that by modeling the technology factors and residents' behaviors together, only 42% of the technological advances would directly contribute to building energy efficiency, while the other 58% requires the collaboration of humans, technologies, management, and the environment. (Zhao et al., 2017) With great potentials in saving energy in building industries, the human dimension has been attracting increasing levels of attention over the last ten years. (Hong et al., 2017)

### 2.2.2 The Culture of Sustainability (COS)

In order to reach full potentials of an energy-efficient building, engaging the citizens of the building is necessary. Building a culture of sustainability (COS) has been shown by previous research to be an effective means to that end. The culture of sustainability can be identified as one in which organizational members hold shared assumptions and beliefs about the importance of integrating economic efficiency, social equity and environmental accountability. (Network for Business Sustainability, 2010) It was found that an organization/company that fostered a culture of sustainability exhibited positive changes in both employee- and organization/company-level sustainability performance. (Galpin et al., 2015) In addition, Eccles et al. compared 90 *high sustainability* firms who adopted solid commitments to social and environmental performance long ago to 90 *low sustainability* firms that did not, and found that the high sustainability firms outperformed their counterparts. These high sustainability firms reaped more financial benefits, and the culture of sustainability became part of their competitiveness in the long run. (Eccles et al., 2012) Since this case study is within a multi-tenant office building, fostering the COS would be both within and among different organizations. Various sustainable practices will be fostered (e.g. visible recycling and compost bins, workstations adorned with bicycle helmets) and engagement plans and activities (e.g. zero-waste potluck, encouraging building citizens to carry reusable mugs, bags, and water bottles) will be carried out in the building. By the end of the five-year project, the goal is to build a culture of sustainability where tenants feel connected to each other and to their vision of the building, while carrying the responsibility of sustainability when staying both inside and outside of the building. (Fernandes et al., 2018)

### 2.2.3 Methods to Study Human Behaviors in Buildings

Multiple methods have been used to study the impacts of human related factors on building performance. The main tools can be classified into four groups: sensors, surveys, observations, and modeling. Sensors are widely used in monitoring the indoor environment data relating to human comfort and behaviors. (D'Oca et al., 2018) Those data include such factors as indoor temperature, humidity, noise, lights, air quality, and people's movement patterns. In 2009, a sensor-based research project was carried out by Dong and Andrews to study human behavior patterns within a typical commercial building. Six different types of sensors were used in this research in order to gather the indoor data mentioned above. Sensors are usually regarded as a simple and spontaneous way to do data collection in a building; however, they do not always give accurate records and the results sometimes need adjustments and estimations. (Dong & Andrews, 2009) Observation is also a common way to collect behavioral data in building related studies. Usually, behaviors that cannot be accurately monitored by sensors will use observations to either correct or compensate for lacking data. A simple example would be noting people's movements within the building. Moreover, using observations to collect data for adaptive behaviors is more efficient and accurate, for example, observing people's use of window blinds to adjust the indoor temperature or turning on/off the lights with the subsequent change of the natural light brightness. Observations are usually quite limited in sample size because the process may not be as continuous as electronic sensors, however, the data from these observations are useful for researchers to identify important behavior changes and key motivations within a building (Yan et al., 2015)

Surveys also serve to collect behavioral data, especially when the data needed cannot be easily monitored or observed. For example, in research related to residential behaviors, surveys can bring back data without offending residents' feelings of privacy. In research studying the indoor environment in Danish dwellings, the researcher sent out survey questionnaires to the potential participants and received 1569 respondents in total for the research. (Andersen et al., 2009) The shortcomings of this method are also known. To some extent, bad data may be given because the participants may misrepresent their behaviors or because they are just not able to recall their behaviors, or participants may even simply respond in the way that they think they are expected to. (Lutzenhiser, 1993; Gunay et al., 2014; Yan et al., 2015)

Lastly, while modeling is not a data collection method per se, it is a widely used technique for analyzing building behavioral data. Specially designed case studies and building simulations are also included in this method. As concluded by Hong et al., there are two main types of modeling: implicit and explicit modeling in building behavior analysis. (Hong et al., 2016) Implicit modeling is based on the data from the physical systems of the building such as windows and elevators, and then uses statistical methods to predict the corresponding key human behaviors. On the other hand, explicit modeling focuses on the monitored behaviors directly. (Hong et al., 2015)

### 2.2.4 Elevator and Stair Studies

Elevators were introduced as a convenient tool for people to travel among floors within a building, especially for high-rise buildings. However, the role of elevators compared to stairs has been controversial for a long time. One study showed that, in a typical 6-floor hospital with six elevators (each of them with stairs beside them), the staff who took stairs to travel among floors saved about 15 minutes per workday compared to those who took the elevators. (Shah et al., 2011) These results may not be applied to other cases since the research was quite limited by factors such as the specific building design, group of people, and method, but it still showed that elevators may not always be an efficient choice for people. Another epidemiologic research showed that the so called "sedentary lifestyle" nowadays among office workers can bring higher risks of disease and mortality. (Manley, 1996) In terms of having a healthier life, stairs seem to be a better choice for those people in order to increase their level of exercise during a busy workday. On another note, studies by Tukia et al. showed that people's choices of using elevators and stairs are closely related to the total energy consumption of their buildings, and four main methods were used by the authors to estimate the annual energy consumption of a typical elevator: 1. permanent installation of a kWh energy meter 2. Using elevator simulators 3. Using energy classification schemes such as VDI 4707-1:2009 and ISO 25745-2:2015 4. Day type-based prediction methods. (Tukia et al., 2016) Measured energy consumption can most assuredly be reduced by people's behavior changes (e.g. using stairs more than the elevators); thus, many researchers have focused on the "keys" that people consider when making those decisions.

### 2.2.5 Factors Affecting the Elevator and Stair Usage

There are multiple factors that may affect people's choices in using elevators and stairs. The first factor is the location and accessibility of the elevators and stairs. A study related to the effects of elevator and stair accessibility was done by Bassett et al. in 2013. Observations were carried out in three buildings, one of which had centrally placed elevators and side stairs while the other two buildings had central stairs and out-of-the-way elevators. The results showed that in the two buildings with central stairs, stair usage percentage was 72.8% and 81.1% for going upstairs and 89.5% and 93.7% for going downstairs, while the stairs usage percentage in the central-elevator building was 8.1% and 10.8% respectively for going upstairs and downstairs. The differences were significant, and a more accessible stair design clearly resulted in a higher stair usage ratio. (Bassett et al., 2013) Furthermore, it can be observed from those data that the direction (e.g. up or down stairs) also affects people's choices since the percentage stair use was 2-8% higher when going downstairs.

In 2001, Boutelle et al. measured effects from interventions such as signs, artwork, and music on stair usage. In their baseline data (before any interventions imposed), one of their findings was that people are more likely to leave using the stairwell than to enter using the stairwell. The research also found that different genders had different stair usage patterns. Their aggregated data (including all the stages of the research: baseline and interventions) showed that women were more likely to use the stairs than men. Since the researchers did not find any evidence that the interventions affected genders differently, gender seemed to be one of the factors affecting stair usage. The effects of gender on elevator and stair usage were also discussed in research by Olander et al. (2008) and Kerr & Carroll (2001). Olander et al. focused on the effects of interventions and Kerr & Carroll researched the demographic characteristics of stair climbing people. Both studies found that males used the stairs more often than females, contrary to the results from Boutelle et al. Since their results were all statistically significant, gender could indeed be a factor with uncertain effects.

Kerr & Carroll's demographic analysis also recorded people of different ages using elevators and stairs. They recorded people with gray hair and/or appearance over 60 years old as "old people", and they found that people of different ages used the stairs and elevators in different ratios. Young people tend to use the stairs more often than older people. (Kerr & Carroll, 2001) An interesting point from the research was that people with large-sized loads (e.g. carrying something larger than a briefcase or medium-sized bag) were also recorded. These results were not displayed in the paper possibly because all people with those loads chose to use the elevators. However, noting the frequency of these "large-load carriers" would be helpful in our research, since these people can be considered to be "elevator required cases" and the carriers may not have had a choice. Other observed people would be automatically grouped into "elevator chosen cases". Studying the stair and elevator use ratios among "people who have a choice" may give us better baseline values.

### 2.2.6 Roles of Interventions in Changing Human Behaviors in Buildings

Interventions can lead to positive behavior changes in building tenants based on previous research. The theoretical potential for energy reduction was identified by researching the typical behavior of employees occupying public university buildings in Germany. This research developed a psychological based intervention program and collected energy consumption, self-reported, and targeted behavior observational data. By gathering data from 15 buildings in four university campuses in Germany, the data after the intervention showed a maximal electricity saving potential of 43% and heating energy saving potential of 10%. (Matthies et al., 2011) In addition, other research using behavioral intervention programs to test the potential energy savings in using office equipment showed that people who received a list of suggestions on how to save electricity and paper modified their behavior more than people in the control group. (Nilsson et al., 2015)

Two main types of interventions were identified for elevator and stair behavior. First, a prominent stair design may cause an increase in the stair-usage rate. In the research conducted by Bassett et al., the main finding was that in a building with central stairs and elevators, more people would use the stairs, than people in a building with side stairs and central elevators. (Bassett, 2013). The other interventions can be regarded as sustainable practices or activities that attempted to encourage people to use stairs more. One study showed that by using banners and messages to increase the attractiveness and visibility of the stairwell in a building, the stair-use rate increased significantly. (van Nieuw-Amerongen et al., 2011) Finally, using other measures such as posters and point-of-choice prompts were identified to have significant effects on improving stair usage in a building (Eves, 2006).

# CHARPTER 3

# Methods

## 3.1 Methods Summary

In this study, the evolution of green buildings and people's behaviors were studied by calculations and analyses based on existing secondary data and collected primary data. The research focused on establishing the baselines of a building's carbon and energy performance as well as tenants' stair/elevator usage. In this case, the research can be regarded as observational research using the transition theory, which aimed to calculate, analyze, and interpret existing trends and changes in order to contribute to our potential decision-making and movements in the future. The research includes two parts: establishing the energy/carbon baselines of the new building; and analyzing elevator and stair usage by tenants in their previous buildings and in the zero carbon building. Thus, there are two corresponding parts of the methods for energy/emission baselines, and elevator and stair baselines. For each, detailed research methods will be illustrated in four main parts: part 1 is the justification of methods used, part 2 explains the data collection methods, part 3 details estimations and assumptions, and part 4 presents the tools for calculation analysis.

Participants in this research included tenants in the case study building and their visitors. In order to obtain their pre-occupancy energy and carbon footprints, the energy consumption and emission data from their previous buildings were collected. A more specific estimation of the energy and carbon profile for each participant was obtained by using two different units to calculate the energy intensity and carbon intensity: energy/carbon per square meter of floor area, energy/carbon per person (per employee or per student). In the calculations, there were certain assumptions and estimations used, such as the population of buildings and the daily energy use behaviors of participants. Since the operational energy and carbon performance values of the building will not be available until after the end of this study, these estimated baseline values were prepared for future research and showed the potential savings that can be achieved.

For the elevator and stair study, the data of tenant elevator and stair usage were collected by making observations and using sensors. A maximum of three observers counted the number of people using stairs and elevators in tenants' previous buildings and the new building. At the same time, key information such as the demographic types, travelling directions, and size of groups in travel was recorded. The use of four people counting sensors collected more data over longer periods than these observations. However, the sensors were recently installed so their reliability for data collection needed to be tested. The accuracy and sensitivity of these sensors were carefully examined and then the sensor-reporting data used to establish the first-year elevator/stair usage baseline.

## 3.2 Energy and Emission Baselines

### 3.2.1 Justification of Methods

The following table shows the measurements and methods that were either directly used, or that inspired the methods used in this study.

| Paper referred to | Indicators and measures | Methods used |
|---|---|---|
| *1.* Ürge-Vorsatz, D., Danny Harvey, L. D., Mirasgedis, S., & Levine, M. D. (2007). Mitigating CO2 Emissions from Energy Use in the World's Buildings. *Building Research & Information*, *35*(4), 379-398. | - Various indicators and measurements: GHG emission-Gt CO2 equivalent, atmosphere CO2 concentration-ppmv, energy consumption in building by sectors-percentage (%) | - Reports from institutions and papers of researchers were reviewed, predominant use of secondary data. |
| *2.* Singh, S., & Kennedy, C. (2015). Estimating Future Energy Use and CO2 Emissions of the World's Cities. *Environmental pollution*, *203*, 271-278. | - Fuel energy use: GJ/cap<br>- Electricity use: MWH/cap<br>- GHG emission: Gt CO2 eq | - Regression model for the cities' energy consumption<br>-Secondary data from UNFCC were used for estimating carbon intensity for countries and regions. If data |

| | | |
|---|---|---|
| | | were not available, the carbon intensity was calculated as an average of all the countries in the same region. |
| *3.* Hoicka, C. E., & Parker, P. (2011). Residential Energy Efficiency Programs, Retrofit Choices and Greenhouse Gas Emissions Savings: A Decade of Energy Efficiency Improvements in Waterloo Region, Canada. *International Journal of Energy Research*, *35*(15), 1312-1324. | - Energy use reduction: GJ<br>- GHG emission reduction: kgCO2 | - Data collected from secondary database (REEP)<br>- Statistical models for data analysis (ANOVA for comparisons among groups) |
| *4.* Ma, J. J., Du, G., Zhang, Z. K., Wang, P. X., & Xie, B. C. (2017). Life Cycle Analysis of Energy Consumption and CO2 Emissions from a Typical Large Office Building in Tianjin, China. *Building and Environment*, *117*, 36-48. | - Energy consumption: GWh and kWh/m2/year<br>- CO2 emission: t and t/m2/year<br>- Energy consumption and CO2 emissions at different life cycle stages: percentages | - Life Cycle Assessment (LCA): construction stage, operation stage and maintenance stage due to the availability of data<br>- Using secondary online databases or data from previous scholars |
| *5.* D'Agostino, D., Cuniberti, B., & Bertoldi, P. (2017). Energy Consumption and Efficiency Technology | - Absolute savings: kWh/year<br>- Relative savings: kWh/m2/year<br>- Percentage of savings: % | - Using secondary databases, especially the Green Building Programme (GBP) database designed for |

|  |  |  |
|---|---|---|
| Measures in European Non-residential Buildings. *Energy and Buildings*, *153*, 72-86. |  | new and existing European non-residential buildings<br>- Post-retrofit phase was compared to the pre-retrofit phase in terms of energy consumption and CO2 emissions |
| 6. Ma, H., Du, N., Yu, S., Lu, W., Zhang, Z., Deng, N., & Li, C. (2017). Analysis of Typical Public Building Energy Consumption in Northern China. *Energy and Buildings*, *136*, 139-150. | - Energy consumption: kWh/ (m2 a)<br>- Carbon Emissions Index: kg/kWh (calculated from the energy consumption values) | - Data from field survey<br>- Sampling and categorizing data (based on building types, end users of energy, etc.)<br>- Statistical methods for data analysis |
| 7. Lu, S., Zheng, S., & Kong, X. (2016). The Performance and Analysis of Office Building Energy Consumption in the West of Inner Mongolia Autonomous Region, China. *Energy and Buildings*, *127*, 499-511. | - Energy consumption: kWh/(m2/year) | - Data collected by a detailed energy audit including basic building information and energy consumption<br>- Interpreting the data from different aspects (e.g., BEC per gross floor area (GFA); special service region (SSR) energy consumption; building energy consumption intensity (ECI) |

Table 3.1 Justification of methods used in setting up an energy/emission baseline

### 3.2.2 Data Collection

For setting up building baselines, energy consumption and carbon emission data in targeted buildings were analyzed. Concerning energy consumption, the research focused on the usage of electricity and natural gas. For carbon emission data, the total greenhouse gas emissions from energy consumption were calculated and converted to CO2 equivalent to simplify the results. First, we examined data at the national level to understand the general trends in building energy consumption/carbon reduction. Then, the provincial data of Ontario were studied in order to investigate the energy consumption/carbon emission levels of our expected tenants among institutional and commercial buildings. The main sources of the data above were national reports and online databases (e.g. IPCC reports, Natural Resources Canada websites). After analyzing the big picture, the research focused on buildings in which our participants initially worked. For tenants from universities, the building in which they previously held an office or studied was used. For tenants from commercial or institutional industries, data from their previous institutional/commercial buildings were used. This case study analyzed the annual data for multiple years (depending on data availability) to describe the energy consumption and carbon emission levels of the tenants in the pre-occupancy stage. Additionally, some supplemental information such as floor areas, and population of the buildings and campuses were acquired for the calculations.

The energy data for buildings in the two universities under scrutiny could be obtained from the energy department, such as electricity and natural gas usage in buildings. However, since the building level data was not available for most of the university buildings, the research needed to use the energy/emission data for the whole campus instead of actual individual buildings. The energy consumption and carbon emission data of other universities were mainly from their annual sustainability reports. In addition, the annual reports included supplemental data such as the total population and area of the campus. Some data representing other tenants could be obtained directly from employees who monitored the energy consumption and carbon emission of buildings within the David Johnston Research + Technology Park (R&T Park). However, the researcher was not able to get permission to access some tenants’ annual energy/emission data by the end of the study.

### 3.2.3 Estimations and Assumptions

Since we did not find evidence that students and employees use different amounts of energy or release different amounts of emissions in those institutional buildings that are occupied by both students and employees, we treated all those people as individuals. The units of the values were therefore energy/person and emissions/person instead of energy or emissions per employee or per student. The units for the values were consequently simplified in the analysis to energy/floor area, energy/person, emission/floor area, and emission/person.

The total number of people working in the building was used as the total number of people who share the energy and carbon footprint of the building, both for the previous tenants' buildings and the new building. The data of institutional and commercial buildings were mainly from obtained their own accounts (e.g. how many people in the organization/company in which year), and campus data were mainly taken from their annual reports. Since building level energy/emission data from universities were not available, the total population and total floor area of the campuses were used for the analysis.

It was assumed that occupants were fully responsible for the energy consumption and emissions of the building. However, all the targeted buildings were either commercial or institutional buildings which were used by occupants only 8-12 hours a day in our study. Thus, the calculated energy/emission per person values are larger than the actual values since the consumption/emissions from non-working hours were also included.

Since all the data sources reported data annually, all the values in the analysis are per-year values.

Energy/emissions data were not available for some of the tenants, so the research assumed that those tenants had similar energy consumption and emissions to other tenants.

### 3.2.4 Analysis

In this section, first, the relationship between energy consumption and GHG emissions was determined since emission data for some buildings were not available. The pre-occupancy energy/carbon footprint of all the previous buildings that tenants occupied was estimated by calculating the building's energy/carbon footprint per m2 and per person.

*For energy consumption*:

Energy consumption per m2 of the building (GJ/m2/year) = total energy consumption of the building (GJ/year) /total floor area of the building (m2)

Energy consumption per person (GJ/person/year) = total energy consumption of the building (GJ/year) / estimated number of people in the building (person)

It should be noted that most energy data reported from the tenants were in different units. For example, electricity consumption was usually reported in kWh and natural gas consumption reported in m3. All of these data were converted into GJ by using the conversion factors provided by Natural Resources Canada for different energy sources: 1 kWh electricity = 0.0036 GJ, and 1 m3 natural gas = 0.0372 GJ energy (Natural Resources Canada, 2013)

*For carbon intensity*:

Based on energy consumption data, CO2 emissions can be calculated as: kg CO2 = E * Coefficient of the year (E) kg CO2/kWh + G * Coefficient (G) kg CO2/m3 (Barker et al., 2007)

Where E is electricity consumed in kWh and G is natural gas consumed in m3. Since the carbon intensity of electricity may change annually, the coefficient may be different for different years.

## 3.3 Elevator and Stair Usage

The research of the elevator and stair usage included both the pre-occupancy (when tenants were still in their previous office buildings) and the post-occupancy stages (when tenants moved into the new building). The goal was to determine whether moving into a building with sustainable features such as central stairs in the atrium can stimulate changes to people’s daily energy use behaviors.

### 3.3.1 Justification of Methods

The following table records the measurements and methods either directly used, or that inspired the methods of this study.

| Paper referred to | Study focuses | Method of research |
|---|---|---|

| | | |
|---|---|---|
| 1.van Nieuw-Amerongen, M. E., Kremers, S. P. J., De Vries, N. K., & Kok, G. (2011). The Use of Prompts, Increased Accessibility, Visibility, and Aesthetics of the Stairwell to Promote Stair Use in a University Building. *Environment and Behavior*, *43*(1), 131-139. | - Increasing the attractiveness of stairs to increase their use<br>- The different effects of interventions on genders | - Observations and video recording for elevator and stair usage data collection<br>- Chi-square test for data analysis |
| 2. Boutelle, K. N., Jeffery, R. W., Murray, D. M., & Schmitz, M. K. H. (2001). Using Signs, Artwork, and Music to Promote Stair Use in a Public Building. *American Journal of Public Health*, *91*(12), 2004-2006. | - Effects of interventions on public stair use<br>- The different effects of interventions and travel direction (up or down) on genders | - Observations in different stages for data collection<br>- One-way ANOVA (analysis of Variance) and two-way ANOVA for data analysis |
| 3. Olander, E. K., Eves, F. F., & Puig-Ribera, A. (2008). Promoting Stair Climbing: Stair-Riser Banners are Better than Posters… Sometimes. *Preventive Medicine*, *46*(4), 308-310. | - Effectiveness of different interventions for encouraging stair usage (banners and posters) | - Observations in different stages for data collection<br>- Logistic regression and chi-square test for data analysis |
| 4. Kerr, J., Eves, F., & Carroll, D. (2001). Six-Month Observational Study of Prompted Stair | - Effects of interventions to improve stair usage rate<br>- The roles of other factors such as gender, age, ethnicity, | - Observations in different stages for data collection |

| | | |
|---|---|---|
| Climbing. *Preventive Medicine*, *33*(5), 422-427. | and bags carried when people make the choice of elevator or stairs | - Logistic regression for data analysis |
| 5.Bassett, D. R., Browning, R., Conger, S. A., Wolff, D. L., & Flynn, J. I. (2013). Architectural Design And Physical Activity: an Observational Study of Staircase and Elevator Use in Different Buildings. *Journal of Physical Activity and Health*, *10*(4), 556-562. | - Stair-usage ratios in differently designed buildings (e.g. central stairs vs side stairs)<br>- the different stair-using ratios when ascending or descending | - Observations in different buildings for data collection<br>- ANOVA test for the data analysis |
| 6.Lee, K. K., Perry, A. S., Wolf, S. A., Agarwal, R., Rosenblum, R., Fischer, S., ... & Silver, L. D. (2012). Promoting Routine Stair Use: Evaluating the Impact of a Stair Prompt Across Buildings. *American Journal of Preventive Medicine*, *42*(2), 136-141. | - The effectiveness of stair prompts for changing stair usage ratio<br>- The long-term trend of stair usage ratios after interventions | - Observations at the screen (a display screen on the wall next to the elevator that indicated the floor location of the elevator) for the data collection<br>- Chi-square test for data analysis |

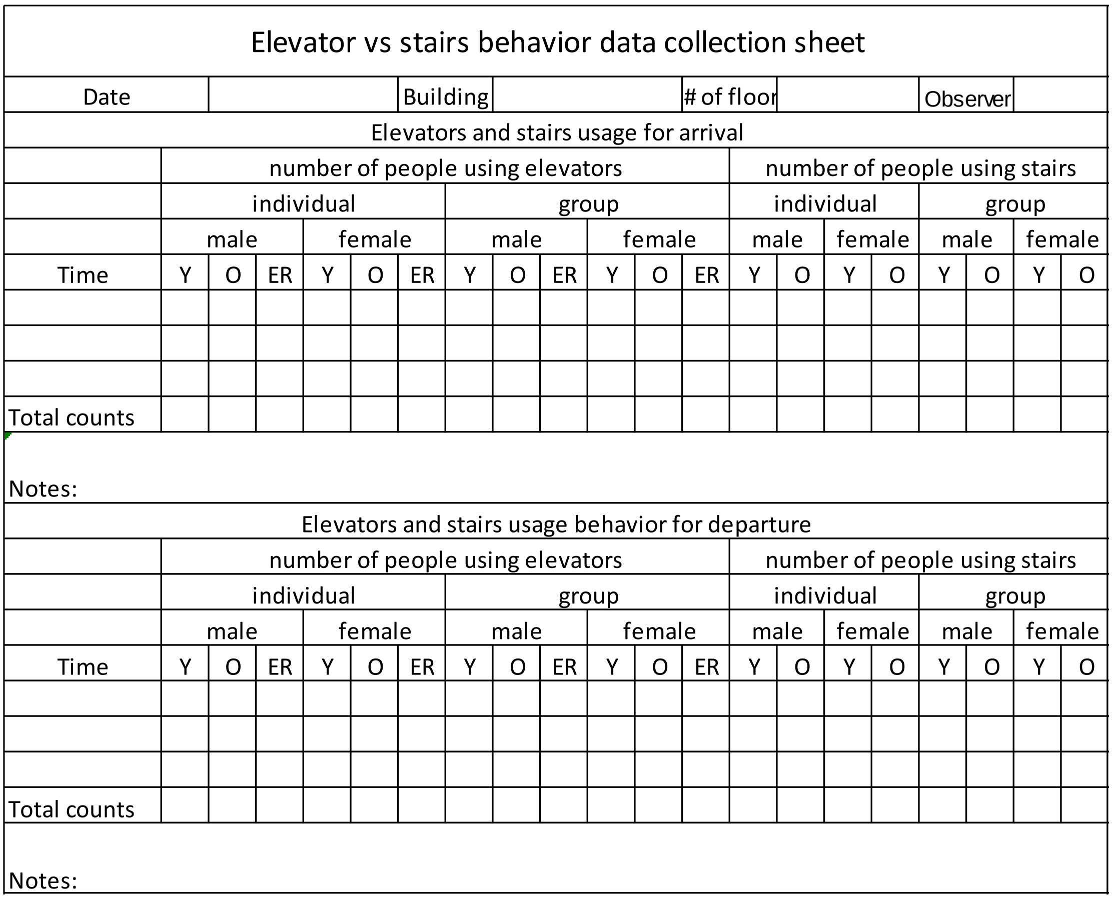
Table 3.2 Justification of methods used in elevator and stair analysis

### 3.3.2 Data Collection

There were three main stages for the elevator and stair data collection and analysis: Stage one: pre-occupancy stage, which mainly focused on the data in tenants’ previous buildings before they moved into the new building; Stage two: pre-engagement stage, which happened after tenants moved in, but before workshops and engagement activities were held; Stage three: post-engagement stage, which collected data after some educational activities were conducted. In addition, the data collection methods in each of the stages were limited due to the availability of sensors. For stage one and stage two, only observational data collection was available. For stage three, both observational and sensor data collection were conducted. The sensors (a total of four people counting sensors) were not available for data collection until April 10th, 2019, such that before these sensors were ready for usage, observational data was collected, and sensor sensitivity tests were conducted in order to check the accuracy of the sensors.

***Stage 1: Pre-occupancy Data***

Since multiple tenants are in the building, and they were in different buildings before they moved in, elevator and stair data were collected through observations in each of the buildings. A standard data collection sheet was designed and used. The following is the excel version of the data sheet.



| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Elevator vs stairs behavior data collection sheet | | | | | | | | | | | | | | | | | | | | |
| Date | | | | | Building | | | | | | # of floor | | | | Observer | | | | | |
| Elevators and stairs usage for arrival | | | | | | | | | | | | | | | | | | | | |
| | number of people using elevators | | | | | | | | | | | | number of people using stairs | | | | | | | |
| | individual | | | | | | group | | | | | | individual | | | | group | | | |
| | male | | | female | | | male | | | female | | | male | | female | | male | | female | |
| Time | Y | O | ER | Y | O | ER | Y | O | ER | Y | O | ER | Y | O | Y | O | Y | O | Y | O |
| | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | |
| Total counts | | | | | | | | | | | | | | | | | | | | |
| Notes: | | | | | | | | | | | | | | | | | | | | |
| Elevators and stairs usage behavior for departure | | | | | | | | | | | | | | | | | | | | |
| | number of people using elevators | | | | | | | | | | | | number of people using stairs | | | | | | | |
| | individual | | | | | | group | | | | | | individual | | | | group | | | |
| | male | | | female | | | male | | | female | | | male | | female | | male | | female | |
| Time | Y | O | ER | Y | O | ER | Y | O | ER | Y | O | ER | Y | O | Y | O | Y | O | Y | O |
| | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | |
| Total counts | | | | | | | | | | | | | | | | | | | | |
| Notes: | | | | | | | | | | | | | | | | | | | | |

Figure 3.1 Elevator and stairs observation sheet

This data collection sheet was used for the pre-occupancy data collection at the previous buildings occupied by the tenants. The sheet included all the factors to be considered in our analysis: age, gender, directions, and group behaviors. In the chart, "Y" indicates "young people", "O" indicates "older people", "ER" indicates "elevator required" for obvious reasons. The "ER" category includes disabled people using wheelchairs, people who carried large-size packages (larger than a briefcase or medium-sized bag), etc.

Three days of data collection were undertaken for each of the tenants' buildings before they moved into the new building. Three time intervals were selected for each tenant based on the most frequent movements in the buildings: morning arrival, lunch break, and end of day departure. Since each of the tenants was in a different building and followed a different work schedule, our data collection time varied among different tenants. A one-hour observation for each of the three time intervals was made by observers, so each day saw three hours of data collection. This was the most efficient method of collecting the largest amount of data in a short period of time. The observers wanted to stay in each of the buildings for the shortest time possible and stay very passive because we did not want their presence to change people's behavior.

Each of the tenants occupied only one floor within the old buildings which made data collection more convenient, however, the different buildings were not designed in the same way. An example of a good design would be the EV3 building of the University of Waterloo, which has a conspicuous central staircase in the atrium with two elevators beside it. In this case, the design not only encourages people to use the stairs, but also is more convenient for the observation of behaviors. Most of the old buildings have elevators in the foyer at the main entrance while stairs are at distant side entrances. Thus, two or three people had to be observing at different entrances to get consistent data for the research. For example, one person was assigned to the main stairs and the other person was assigned to the elevators to record the data separately for the same period of time.

### ***Stage 2: Pre-engagement Data***

Within the zero carbon building, the Sustainable Waterloo Region (SWR) staff held multiple sustainability engagement workshops for the tenants' employees. Through these workshops people learned about sustainability and potential changes to their daily behaviors. Although stair usage was not the focus of the workshops, as it was one of several potential pro-environment actions, the elevator and stair usage pattern can provide an indicator of the effectiveness of these workshops to stimulate change. For this study, the purpose was to discover whether moving into a green building with a prominent staircase altered people's behaviors, comparing stage 1 and stage 2, or whether an educational program would make bigger changes, comparing stage 2 and stage 3.

In stage 2, the same data collection sheet (Figure 3.1) was used. Since it is a three-floor building, and it has both central main stairs and central elevators , the observers were placed one on the second floor and one on the third floor to make their observations. The data collection was also divided into three time periods: morning arrival (8.30-9.30 am), lunch break (12-1 pm), and end-of-day departure (4-5 pm). Observations were done on three days: December 3rd, 4th, and 5th for the data collection in this stage.

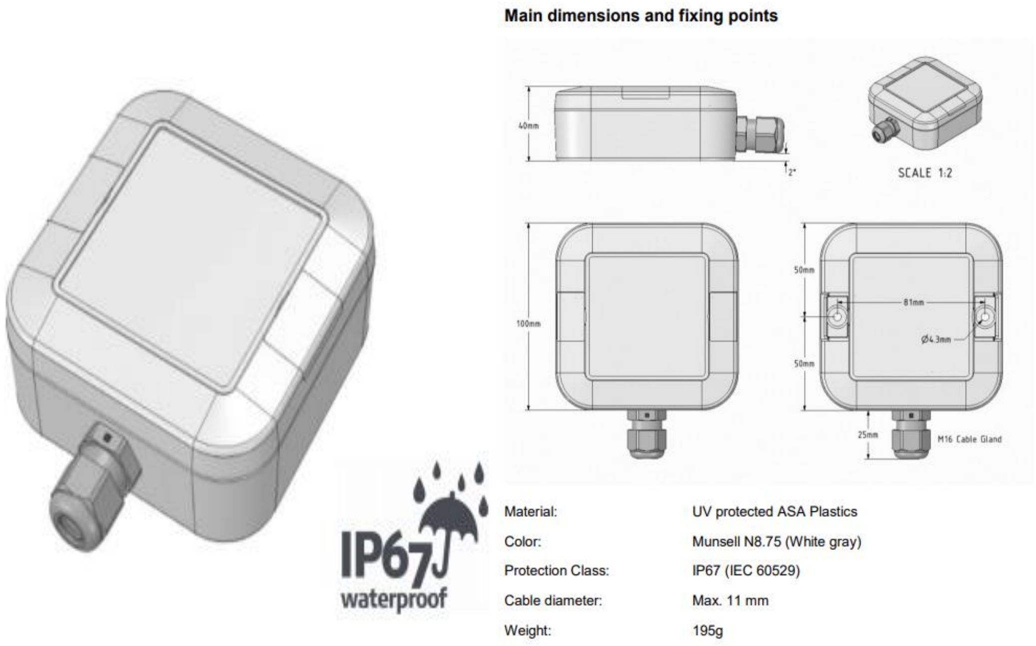
### ***Stage 3: Post-engagement data***

After a couple of engagement workshops took place, a third round of data collection was undertaken for elevator and stair usage. Since the engagement plan was continuous and people's behaviors may change over time, several rounds of data collection were done in this stage in order to study the tenants' behavior changes over time. Four people counting sensors were installed for the data collection. Using sensors for data collection involving people counting is new in elevator and stair usage research, so the analysis section highlighted the limitations of this method and potential applications for future research.

Four rounds of observations were conducted during this stage. The first round was on January 21st after the first engagement activity was completed, and then the second round of observation was on April 11th and April 18th. The third round was on May 1st and May 8th while the last round was done on May 15th and May 22nd. The same data collection sheet (Figure 3.1) was used. The four sensors arrived on April 10th, so subsequent to this date, researchers were able to test the accuracy and sensitivity of all the sensors and try to improve their recording accuracy. In this manner, observational data collection was done simultaneously with sensor accuracy tests. This method allowed obtaining observational data and sensor counting data on the same dates, saving time for the data collection and ensuring that the data were easier to compare (e.g. use the same-day data to test sensor accuracy). A single observer conducted the post-occupancy data collection.

The sensors used by the case study building were “PCR2”, radar-based people flow sensors. The PCR2 device is based on the principle of approximation and distance from the Doppler-Radar sensor, so that people can be counted from all directions. (Parametric, 2018b)

Below is an illustration of the sensor:



| | |
|---|---|
| Material: | UV protected ASA Plastics |
| Color: | Munsell N8.75 (White gray) |
| Protection Class: | IP67 (IEC 60529) |
| Cable diameter: | Max. 11 mm |
| Weight: | 195g |

Figure 3.2 A typical PCR2 sensor with main dimensional information
(Source: Parametric. (2018a). PCR2-OD Datasheet. PCR2 LoRaWAN™ Radar People Counter Outdoor)

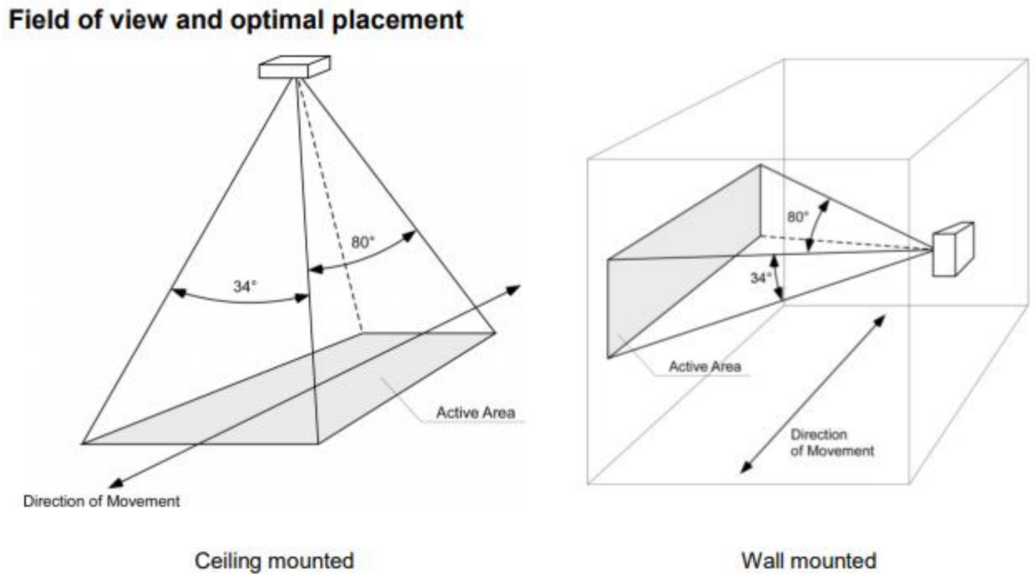


Figure 3.3 Mounting instructions for the sensors

(Source: Parametric. (2018a). PCR2-OD Datasheet. PCR2 LoRaWAN™ Radar People Counter Outdoor)

As displayed above, the size of the sensor is similar to a palm of an adult’s hand. The left half of Figure 3.3 shows the front of the sensor, indicating that the sensors’ range is 40-degree angle left and right, and 17-degree angle up and down from the center of the sensor. The sensors were consequently set up on the glass wall facing the inside of the stairs to capture people’s movements. The plus and minus 40-degree angle was parallel to the ground in order to cover a wider range of the stairs (as it is shown in Figure 3.3, wall mounted orientation). The elevator sensors were located on top of the elevator doors. The orientation of the sensors was adjusted to face the ground, placing the 40-degree angle scope both outside and inside the elevators. This is because the sensors can measure movements from all directions, but can only export the data from the left-right side with the lights (as shown in Figure 3.3, ceiling mounted orientation). This placement may have engendered some problems. The 40-degree angle covered area was relatively large, making it more likely that the sensor would count random people walking by (but not taking the elevator), making the collected data less reliable. This will be further explained in the accuracy test sections.

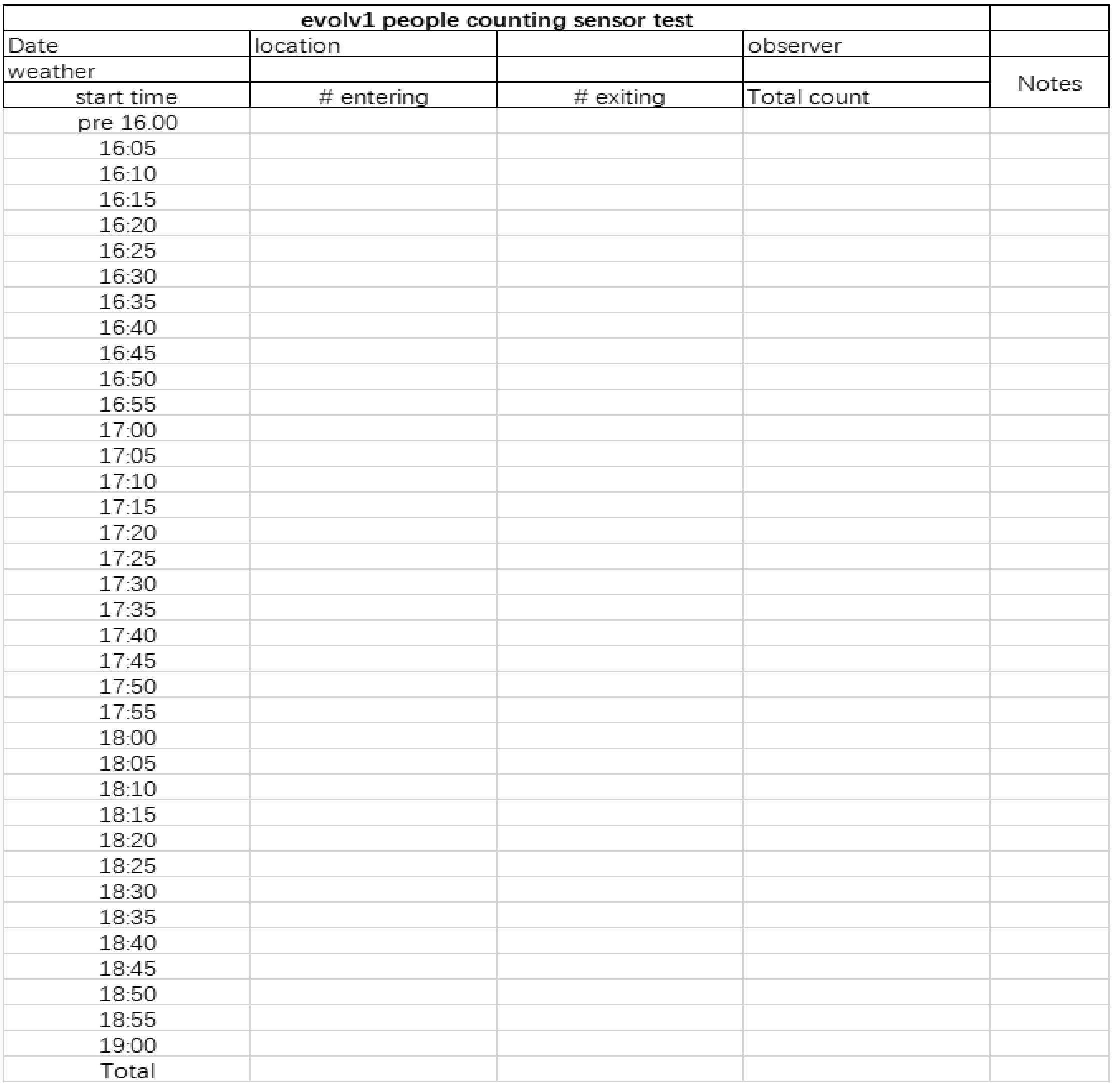
There were four sensors for the elevators and stairs in the building. One sensor for each of the elevators and two sensors for the stairs. Since the building has two elevators and three stairs (one central main staircase and two side stairs) with three floors, the observer had to move the stair sensor around to ensure it would count all the traffic within the building. Here, the data from the two elevators and the data from the central stairs were used for the observational data analysis, while the data from all the stairs and elevators were used for the sensor-reported data analysis. (Since the research was a comparative study and the data of stage one and stage two were mostly elevator and main staircase data, it was better to keep things consistent. However, for the sensor data, only the new building used this data collection method. It was therefore reasonable to include data from all the stairs and elevators to make the elevator and stair usage profile as complete as possible in the building.)

Based on the information from the producer, the sensors are radar-based so they may miss some data when people are too close to each other (closer than 2 meters) or when there was a group of people walking by at the same time. The following sensor tests were conducted in order to study collection errors of the sensor-reported data.

### *First Test of the Sensor Accuracy*

Upon the arrival of the first people counting sensor, a sensor accuracy test was conducted to see whether sensor data matched the data from observational counts. The sensor was first placed on the wall inside the building on the side of the atrium door to the car park and captured the traffic through that door. An observer counted people for two days on February 25th and February 26th.The observation time started around 8 o’clock in the morning and ended at 12.20 pm. After gathering the data from the observations, sensor data were obtained from the online database – eleven-x, which stored the data captured by the sensor. The two data sets were compared to see how well they matched.

The same data collection procedures were repeated after moving the sensor to the side door by the loading bay. This time, the observer did the observation on February 27th and 28th, from 4 pm to 7 pm when people were leaving the building at the end of the day. Sensor data were obtained and compared to observation data. The sample data collection sheet is as below:



| evolv1 people counting sensor test | | | | |
|---|---|---|---|---|
| Date | location | | observer | |
| weather | | | | Notes |
| start time | # entering | # exiting | Total count | |
| pre 16.00 | | | | |
| 16:05 | | | | |
| 16:10 | | | | |
| 16:15 | | | | |
| 16:20 | | | | |
| 16:25 | | | | |
| 16:30 | | | | |
| 16:35 | | | | |
| 16:40 | | | | |
| 16:45 | | | | |
| 16:50 | | | | |
| 16:55 | | | | |
| 17:00 | | | | |
| 17:05 | | | | |
| 17:10 | | | | |
| 17:15 | | | | |
| 17:20 | | | | |
| 17:25 | | | | |
| 17:30 | | | | |
| 17:35 | | | | |
| 17:40 | | | | |
| 17:45 | | | | |
| 17:50 | | | | |
| 17:55 | | | | |
| 18:00 | | | | |
| 18:05 | | | | |
| 18:10 | | | | |
| 18:15 | | | | |
| 18:20 | | | | |
| 18:25 | | | | |
| 18:30 | | | | |
| 18:35 | | | | |
| 18:40 | | | | |
| 18:45 | | | | |
| 18:50 | | | | |
| 18:55 | | | | |
| 19:00 | | | | |
| Total | | | | |

Figure 3.4 Sensor accuracy test observation sheet for the side entrance.

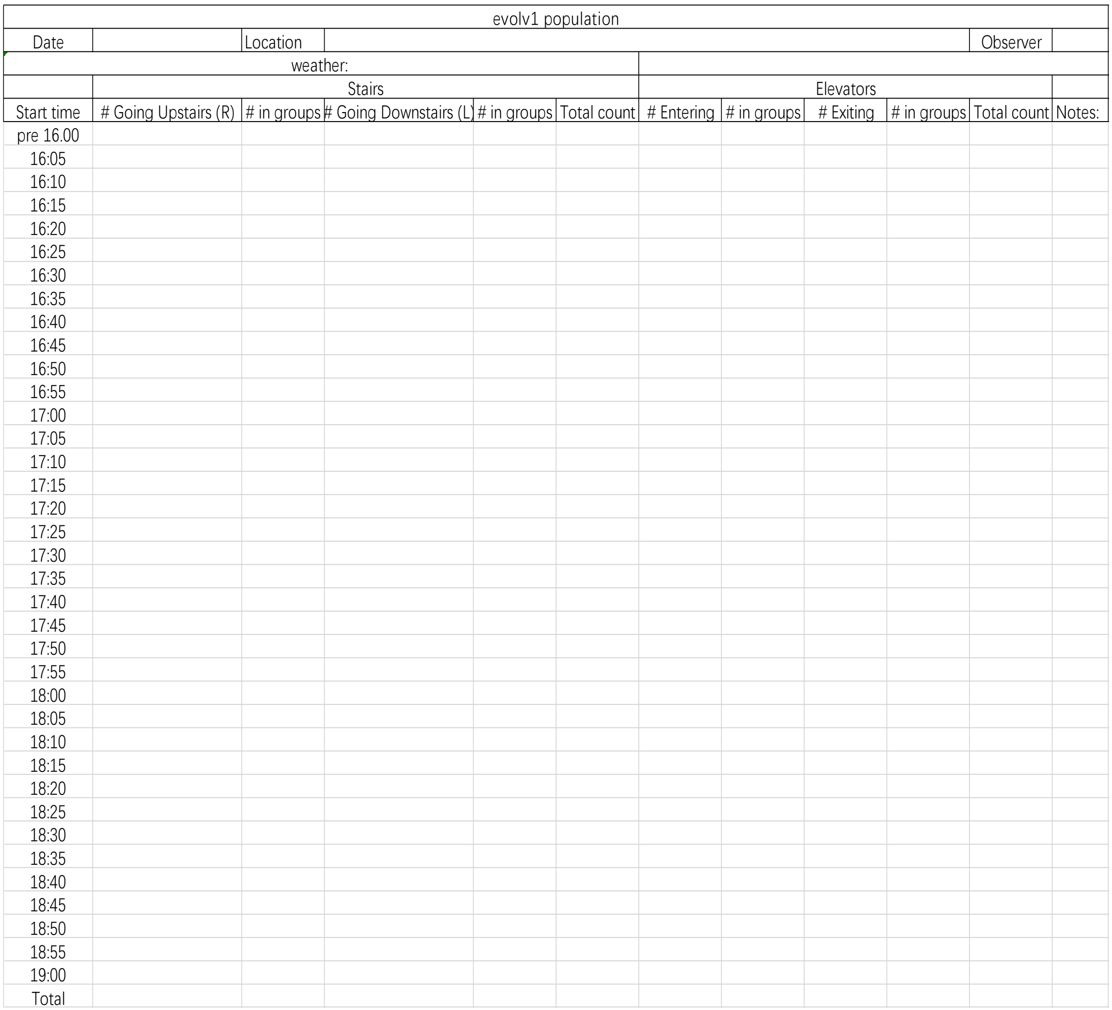
The sheet used for the main entrance and the one for the side entrance were slightly different. Here in Figure 3.4, the number of people in groups was not recorded in separate columns as it was for the main entrance observation. Instead, the people moving in groups were recorded in the “notes” column. This was due to the fact that the side entrance usually has much less traffic than the main one, so not as many groups would be observed (Indeed, from the 3-hour observation, only 2 groups were recorded). This was also the reason why we did the test for two entrances. Since the traffic was different, it would be interesting to see whether fewer people and fewer disturbing factors (e.g. fewer groups) allowed more accurate sensor data collection.

For the test, usually one specific time period was selected, for example, morning 8 am to 12.20 pm or late afternoon 4-7 pm. These are indeed the times in an office building when people used the doors most often. In addition, during those time intervals most people had a specific moving direction. For example in the morning people came into the building more frequently and in the late afternoon people mostly left the building. Since the sensor can also record the direction of people's movements, it was easier for the observer to tell whether the sensor was indeed recording the correct direction.

The main purpose of testing the sensors on the doors first (instead of the stairs or elevators) was to compare these initial results to the accuracy test results later (for stairs and elevators) in order to see when the sensors were more accurate and to identify the potential disturbing factors. In this test all the people moved almost perpendicular to the sensors' sensing area, and the sensor faced people's walking path directly at a right angle. Later, the sensor was relocated to the stairs and then elevators, so it could be determined whether sensor accuracy was effected by a change in orientation.

### *Test of the Stair Sensor Accuracy*

The observer moved one sensor to the central stairs between the second and the ground floor and set it up on the left (when walking upstairs) glass wall of the stairs facing the inside of the stairs to capture people's movements. Another sensor was used to collect data for third floor stair usage and positioned in similar way between the second and third floor stairs on the glass wall (since the location was different, the accuracy might be different as well because the sensor was facing a more populated area). While the sensor captured people going up or down the stairs, observations were done for a specific time interval during one day and the numbers were compared to the sensor reported data during the same time interval. The following is the data collection chart used for this process.



| evolv1 population | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | | Location | | | | | | | | Observer | |
| weather: | | | | | | | | | | | |
| | Stairs | | | | | Elevators | | | | | |
| Start time | # Going Upstairs (R) | # in groups | # Going Downstairs (L) | # in groups | Total count | # Entering | # in groups | # Exiting | # in groups | Total count | Notes: |
| pre 16.00 | | | | | | | | | | | |
| 16:05 | | | | | | | | | | | |
| 16:10 | | | | | | | | | | | |
| 16:15 | | | | | | | | | | | |
| 16:20 | | | | | | | | | | | |
| 16:25 | | | | | | | | | | | |
| 16:30 | | | | | | | | | | | |
| 16:35 | | | | | | | | | | | |
| 16:40 | | | | | | | | | | | |
| 16:45 | | | | | | | | | | | |
| 16:50 | | | | | | | | | | | |
| 16:55 | | | | | | | | | | | |
| 17:00 | | | | | | | | | | | |
| 17:05 | | | | | | | | | | | |
| 17:10 | | | | | | | | | | | |
| 17:15 | | | | | | | | | | | |
| 17:20 | | | | | | | | | | | |
| 17:25 | | | | | | | | | | | |
| 17:30 | | | | | | | | | | | |
| 17:35 | | | | | | | | | | | |
| 17:40 | | | | | | | | | | | |
| 17:45 | | | | | | | | | | | |
| 17:50 | | | | | | | | | | | |
| 17:55 | | | | | | | | | | | |
| 18:00 | | | | | | | | | | | |
| 18:05 | | | | | | | | | | | |
| 18:10 | | | | | | | | | | | |
| 18:15 | | | | | | | | | | | |
| 18:20 | | | | | | | | | | | |
| 18:25 | | | | | | | | | | | |
| 18:30 | | | | | | | | | | | |
| 18:35 | | | | | | | | | | | |
| 18:40 | | | | | | | | | | | |
| 18:45 | | | | | | | | | | | |
| 18:50 | | | | | | | | | | | |
| 18:55 | | | | | | | | | | | |
| 19:00 | | | | | | | | | | | |
| Total | | | | | | | | | | | |

Figure 3.5 Sensor accuracy observation chart.

The observation was three hours a day over two days in total. End-of-day hours were picked: 4 pm - 7 pm for the observations when people were mainly leaving the building. The number of people going downstairs, upstairs, entering the elevators and exiting the elevators was recorded, and then compared to the sensor reported data. The sensor can also record movement direction separately. It was programmed to skip recording the first five minutes after installation and report the number of people counted every five minutes thereafter. At this stage, the elevators did not have sensors on them. Since observers were already counting the people leaving the building, the elevator usage data were collected at the same time. While those data cannot be compared to the sensor data, they are still post-engagement data that can be compared to the observational data from the first two stages, and used in the observational data analysis.

### *Test of the Elevator Sensor Accuracy*

The four sensors were set up on the two elevators and central stairs. One sensor for each of the elevators, and one sensor between the ground floor and the second on the main stairs, and another between the second floor and the third floor. The sensor on the left (when facing the elevator door from the outside) elevator was labeled “sensor elevator #1” (E#1), the sensor on the right elevator was labeled “sensor elevator #2” (E#2), the stair sensor between the ground and the second floor was labeled as “sensor stairs #1” (S#1), and the stair sensor between the second and the third floor was labeled as “sensor stairs #2” (S#2). Since the sensors could be moved to other locations for data collection (e.g. side stairs), those same labels were re-used for the sensors throughout the entire research in order to avoid too many different labels. This time, all the four sensors were tested at the same time. Since sensor accuracy on stairs had already been tested, the focus was on elevator observation and sensor data comparison. However, three of the four sensors were new arrivals, so it was in fact necessary to make sure all these new sensors worked properly.

The observation was done over two days at complementary times. On the first day, 8 hours of observation was distributed as: 9 am - 11 am, 11:30 - 1:30 pm, 2:30 pm - 4:30 pm, and 5 pm - 7 pm. On the second day, the 8 hour distribution was: 8 am - 10 am, 10:30 am - 12:30 pm, 1 pm - 3 pm, 3:30 pm - 5:30 pm. In total, the hours covered an entire workday from 8 am to 7 pm for the organizations in the building. The two observation days were April 11th and April 18th, which were both Thursdays. The sample data collection sheet (one two-hour time interval) is presented below:

Sensor accuracy test sheet

| time | E#1 | | | | E#2 | | | | S#1 | | | | S#2 | | | | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | in | group | out | group | in | group | out | group | up | group | down | group | up | group | down | group | |
| 9:05 AM | | | | | | | | | | | | | | | | | |
| 9:10 AM | | | | | | | | | | | | | | | | | |
| 9:15 AM | | | | | | | | | | | | | | | | | |
| 9:20 AM | | | | | | | | | | | | | | | | | |
| 9:25 AM | | | | | | | | | | | | | | | | | |
| 9:30 AM | | | | | | | | | | | | | | | | | |
| 9:35 AM | | | | | | | | | | | | | | | | | |
| 9:40 AM | | | | | | | | | | | | | | | | | |
| 9:45 AM | | | | | | | | | | | | | | | | | |
| 9:50 AM | | | | | | | | | | | | | | | | | |
| 9:55 AM | | | | | | | | | | | | | | | | | |
| 10:00 AM | | | | | | | | | | | | | | | | | |
| 10:05 AM | | | | | | | | | | | | | | | | | |
| 10:10 AM | | | | | | | | | | | | | | | | | |
| 10:15 AM | | | | | | | | | | | | | | | | | |
| 10:20 AM | | | | | | | | | | | | | | | | | |
| 10:25 AM | | | | | | | | | | | | | | | | | |
| 10:30 AM | | | | | | | | | | | | | | | | | |
| 10:35 AM | | | | | | | | | | | | | | | | | |
| 10:40 AM | | | | | | | | | | | | | | | | | |
| 10:45 AM | | | | | | | | | | | | | | | | | |
| 10:50 AM | | | | | | | | | | | | | | | | | |
| 10:55 AM | | | | | | | | | | | | | | | | | |
| 11:00 AM | | | | | | | | | | | | | | | | | |

Figure 3.6 Elevator and stair sensor accuracy test data collection sheet.

In this sheet, the number of people using elevators or stairs and their directions (in/out, up/down) was recorded. The group column was used to record the number of people in a group and how many groups there were. The data were recorded at 5-minute time intervals.

### *Further Elevator Sensor Accuracy Tests*

By looking at the differences between the sensor data obtained and the observations, sensor accuracy could be estimated. If differences appeared, a further elevator accuracy test would be conducted. The first step was analyzing the consistency of data from the sensors. If the sensor-reported data for each of the locations were consistent, then the observed errors for one day could be used to estimate the overall errors for a week or a month.

First, it was necessary to establish a data collection schedule in order to obtain the data available for the consistency analysis.

| Location | Number of sensors | Collection length |
|---|---|---|
| Ground floor two elevators | 2 in total, one for each elevator | 1 week (5 workdays) |

| | | |
|---|---|---|
| Second floor two elevators | 2 in total, one for each elevator | 1week (5 workdays) |
| Third floor two elevators | 2 in total, one for each elevator | 1 week (5 workdays) |
| Second floor central stairs | 1 | 7 weeks (31 workdays) |
| Third floor central stairs | 1 | 7 weeks (31 workdays) |
| East side stairs second floor | 1 | 1 week (5 workdays) |
| East side stairs third floor | 1 | 1 week (5 workdays) |
| West side stairs second floor | 1 | 1 week (5 workdays) |
| West side stairs third floor | 1 | 1 week (5 workdays) |

Table 3.3 The data available for the consistency analysis

Then, for each of the locations, correlation tests (regression tests) were done to see whether stair and elevator usage varied by weekday or by week of the month.

| Locations | Analysis of correlations | Counting number summary | Counting graph displayed |
|---|---|---|---|
| Ground floor two elevators | | | |
| Second floor two elevators | | | |
| Third floor two elevators | | | |
| Second floor central stairs | | | |
| Third floor central stairs | | | |
| East side stairs second floor | | | |
| East side stairs third floor | | | |
| West side stairs second floor | | | |

| | | | |
|---|---|---|---|
| West side stairs third floor | | | |
| | | | |

Table 3.4 Sample results sheet for the consistency analysis of sensor data

For the consistency analysis, if the data were within a week, then regression tests were conducted in order to determine whether the counts from the sensors are in fact related to the day of the week; if the data were over more than a week (e.g. data for central stairs), then after the regression tests for data within each week, ANOVAs were used to determine whether the counting numbers varied among different weeks.

If the data from the sensors during one week can be regarded as consistent, it can be assumed that potential errors happened consistently in every day’s sensor recording. Consequently, the sensors could be adjusted to prevent them from consistent error. The possible adjustments are summarized as follows:

1. Adjust the orientation of the elevator sensor to reduce disturbances (e.g. rotating the sensors inwards to adjust the covered angles).
2. Adjust the location of the elevator sensor to reduce disturbances (e.g. moving the sensor from the center to the side to adjust the covered area).
3. Corresponding tests and analysis based on the changes above.

The detailed plans for further tests were based on the main findings from the previous accuracy tests and observations and were included in the analysis section.

### *Test of the sensor sensitivity*

In addition to comparing the total numbers from the observations and counters, it was also important to know the types of errors the sensor makes. Two observers positioned the sensor facing an empty wall and then they walked in front of it following the protocol below:

1. One person walked from the left side of the sensor to the right side, three times at a medium walking pace.
2. One person walked from the left side of the sensor to the right side, one time at a fast walking pace.
3. One person walked from the left side of the sensor to the center, stopped there for couple of seconds and then departed to the right.

4. Two people walked very closely together, about 10 cm away from each other, from the left side of the sensor to the right side (very close).
5. Two people walked from the left side of the sensor to the right side, one person totally blocking the other (overlapped) to test whether they were counted as a single person.
6. One person walked from the left side of the sensor to the right side while the other person walked from the right side of the sensor to the left side. The two people overlapped at the ***center*** of the sensing area.
7. One person walked from the left side of the sensor to the right side while the other person walked from the right side of the sensor to the left side. The two people overlapped ***outside*** the center of the sensing area.

The tests above were enough for the two stair sensors because the stair sensors had almost the same orientation as the test sensors, so it can be assumed that any sensor mistakes or errors in the above tests could be generalized to the stair sensors.

The following tests were done for the elevator sensors. Since these sensors were placed facing down to the ground, and the angles covered a wide range in and out of the elevators, the study wanted to test the types of errors that could be made by the sensors. The details of the tests are as below:
1. Walking from left (when facing the elevator doors from the outside) to right with the walking route parallel to the elevator doors (Simulating people walking by the elevators from left to right)
2. Walking from right (when facing the elevator doors from the outside) to left with the walking route parallel to the elevator doors (Simulating people walking by the elevators from right to left)
3. Walking towards the elevator door but not entering the elevator, and then leaving very quickly (Simulating a person approaching and pressing the button but then deciding not to take the elevator)
4. Walking towards the elevator door but not entering the elevator, and then staying for approximately10 seconds (Simulating a person coming and waiting for the elevator to arrive).

For all the tests above, the reactions from both elevator sensors were recorded. Since these two elevators are close to each other, walking by one elevator to take the other may cause the sensor to react. No tests were done by staying inside the elevator since our sensors were outside of the elevators and the doors would close fast, disturbance from the inside should be relatively small.

Notes were taken at the end of each test and the detailed results will be displayed in the analysis section.

### 3.3.3 Estimations and Assumptions

Since the observations were limited by different factors such as time and resources, the following estimations and assumptions were made in order to make better use of the collected data:

1. Since the data for the pre-occupancy observations were collected from different buildings and each building has its unique orientation and design (e.g. elevators and stairs apart from each other, main stairs versus side stairs, etc.), the observations may not cover all the elevators and stairs at the same time due to the use of only two or three observers. Consequently, the data from the main stairs and elevators (e.g. central stairs if the building has them, if not side stairs observed by two people) were used to analyze behaviors of the tenants. For consistency, all the data used for the pre-occupancy elevator and stair analysis were main elevator and stair data. Both observational and sensor-recording data was used for the post-occupancy stage. The observational data were also from the central stairs and elevators in the case study building in order to make the results comparable to the pre-occupancy stages. However, the study will use all the stairs and elevators when setting up the new stair/elevator usage baseline in the new building by using sensor-recording data.
2. The observers counted people for three hours per building per day for the pre-occupancy observations: arrival, lunch, and departure. However, for arrival and departure, it cannot be guaranteed that all the tenants in the building were observed, since people may arrive/leave early/late. It was assumed that most of the tenants would follow a daily schedule and observers recorded them during the data collection.
3. A few people (n=1-3 per day) took their bicycles into their offices when they came to work, and this was recorded as “elevator required” (ER) for obvious reasons. It should be noted that using elevators in a building consumes far less energy than the fuel consumed by cars and busses to arrive at work. Still, it’s interesting to see the trade-off between a sustainable commuting behavior and a sustainable energy-using behavior in buildings that don’t have secure bicycle parking sites.
4. The presence of the observers may affect people’s behaviors. The observers made passive observations and did not engage people in conversation. However, when some

people saw the observers standing beside the stairs or elevators with data collection sheets, they were curious and asked what the observers were doing. A simple explanation was provided, which could in turn influence their behaviors. For example, some staff would wave to us when they took the stairs during our observations.

5. People with heavy loads (e.g. people carrying suitcases, big bags, or maintenance staff with ladders or other equipment) were categorized as part of an "elevator required" (ER) group. Since they *needed* to use the elevators instead of *choosing* to use elevators, they are excluded from some of the behavior choice analyses later in the paper.
6. The sensors are battery-powered. It was consequently necessary to replace the battery when it was low, which could result in some missing data (approximately one 5-minute interval each time the battery was replaced). Four people-counting sensors were used, and in order to minimize data loss a rotation using six batteries was established. Researchers recharged each of the batteries in an office in the building. A detailed sample battery recharging schedule can be found in Appendix A.
7. Since the case study building has two upper floors, two elevators and four entrances, the four sensors cannot record all the traffic at the same time. The sensors were moved to different positions for the population counting and the resulting data was combined to obtain a comprehensive picture.
8. It was assumed that all the sensors are identical. These four sensors should indeed have identical algorithms for their operation. However, our observations and data comparisons brought to light that some of the sensors had some data missing for unknown reasons, and some sensors reported data in 10 minute intervals instead of 5 minute intervals. Those differences were standardized in the analysis.

### 3.3.4 Analysis

Various statistical tests were used for the data analysis. The linear regression test, one-way ANOVA test, two-way ANOVA test, and chi-square test were the four main tests used.

# CHARPTER 4

# Results

## 4.1 Building Baselines

### 4.1.1 Energy/Emissions in Buildings

This section starts from the overall picture of the global and national energy and emission trends and then narrows down to the energy and emission analysis in specific buildings.

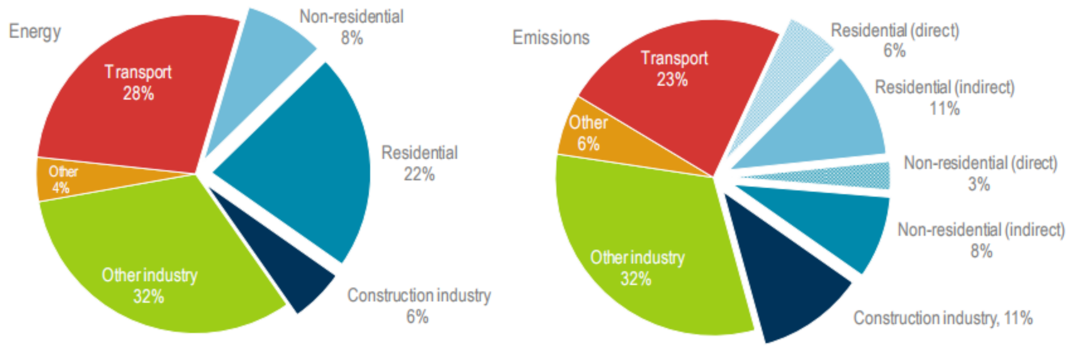


Figure 4.1 Global share of buildings and construction final energy use and emissions, 2017.

(Sources: Derived from IEA (2018a), World Energy Statistics and Balances 2018, www.iea.org/statistics and IEA Energy Technology Perspectives buildings model, www.iea.org/buildings.)

Note: The construction sector included the main industrial manufacturers for the construction materials of the building (e.g. steel, cement, glass.)

In 2017, buildings (non-residential, residential, and construction industry) accounted for 36% of the world's total end use energy, and 39% of process-related emissions. As indicated by the pie charts, buildings were the biggest energy consumer and emission contributor globally. This makes it one of the most important target areas for taking actions against climate change.

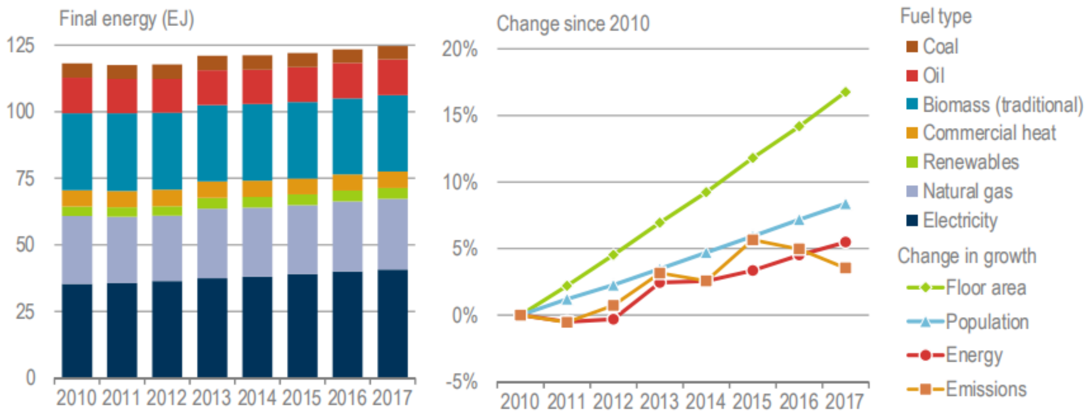


Figure 4.2 Global building industries final energy use by fuel type and percentage change, since 2010.

Source: Derived

from IEA (2018a), World Energy Statistics and Balances 2018, [www.iea.org/statistics](www.iea.org/statistics)

and IEA Energy Technology Perspectives buildings model, [www.iea.org/buildings](www.iea.org/buildings).

Note: Biomass (traditional) refers to conventional solid biomass (e.g. charcoal and wood or agricultural resources). Renewables included solar thermal technologies and modern biomass resources (e.g. pellets and biogas). The results were not normalized by weather data, so shifts in the energy use may be affected by changes in weather conditions. (2018 Global Status Report, IEA)

Biomass in the graph mainly consisted of that used by inefficient heating equipment. The relatively large percentage in the graph is due to the hefty amount of biomass consumption in developing countries. In Canada, biomass only accounted for 1.7% of the countries' total capacity and 1.9% of total generation in 2015 (12,161 GWh electricity generated). (Government of Canada, 2019)

From 2010 to 2016, the global final energy consumption in buildings increased by about 5%, which indicated that the improvements in building energy efficiency did not offset the additional energy use brought about by the increase of building floor area and population. However, a positive signal was that energy demand growth was lower than the floor area increase (about 17% from 2010 to 2017). The shift to energy-efficient technologies in buildings is largely responsible for that phenomenon. For example, the use of light-emitting diodes (LEDs), heat pumps, and improvements in building envelopes all played important roles in offsetting the growth of energy demand.

The demand for electricity increased 15% during the period while the renewable energy used in buildings increased 14%. This showed that the shift to electricity was not a totally clean energy transition, and electricity production still partially relied on fossil fuels. Natural gas consumption increased by 5% and supplanted part of the less-efficient energy sources such as coal, whose demand decreased by 8%.

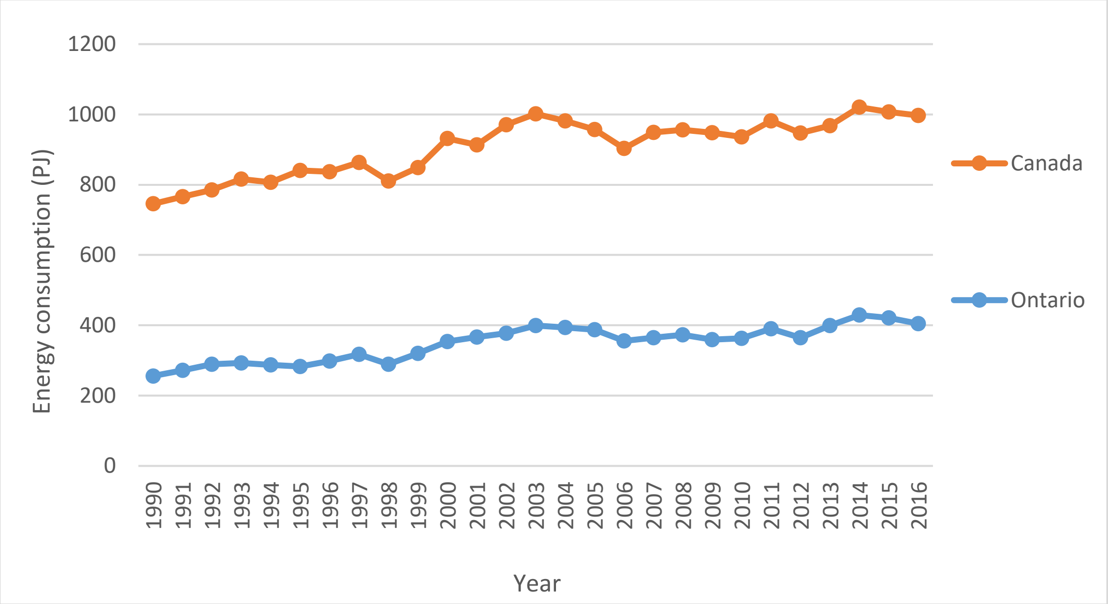


Figure 4.3 Energy consumption by commercial and institutional sectors in Canada and Ontario, 1990-2016.

Source: Data retrieved from Natural Resources Canada: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm

Note: The energy sources included electricity, natural gas, light fuel oil and kerosene, heavy fuel oil, steam, and other (including coal and propane). The commercial and institutional industries included: wholesale trade, retail trade, transportation and warehousing, information and cultural industries, offices, educational services, health care and social assistance, arts, entertainment and recreation, accommodation and food services, and other services. The buildings accounted for the most of the consumption (except in Public Admin.).

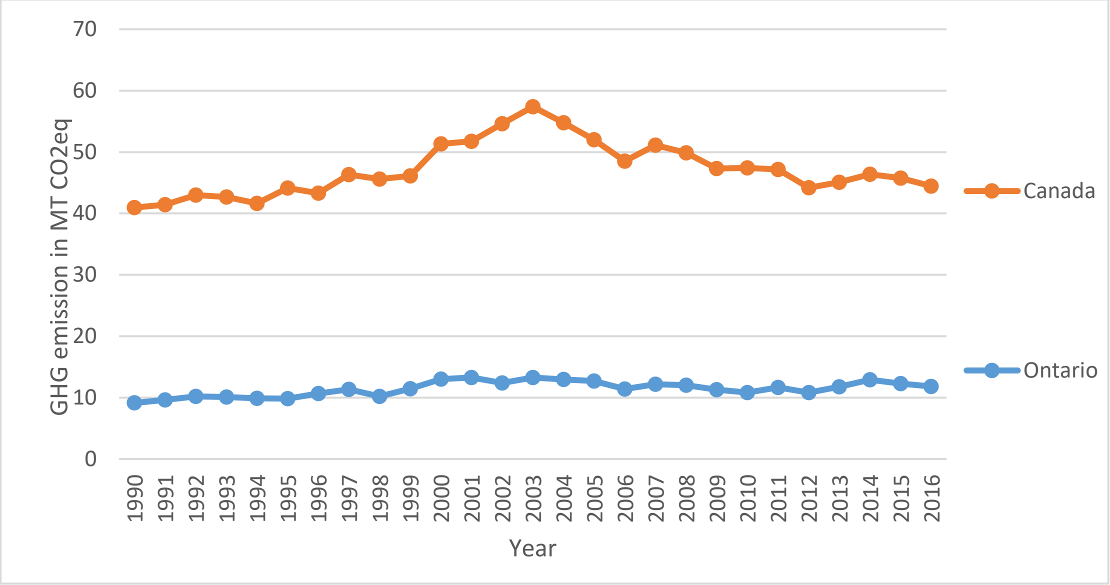


Figure 4.4 GHG emissions from commercial and institutional industries in Canada and Ontario, 1990-2016.

Source: Data retrieved from Natural Resources of Canada: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm

Note: The Ontario data did not include emissions from electricity production activities. For the emission trend of Canada, it can be observed that the emissions of the country went up and peaked in 2003 and then showed a gradual decrease. There were multiple reasons for the trend. First, an increase of energy prices emerged at year 2003, which caused energy demand reduction in both residential and commercial buildings. Second, the use of low emission energy sources increased and further reduced the emission of GHG. (Environment Canada, 2008)

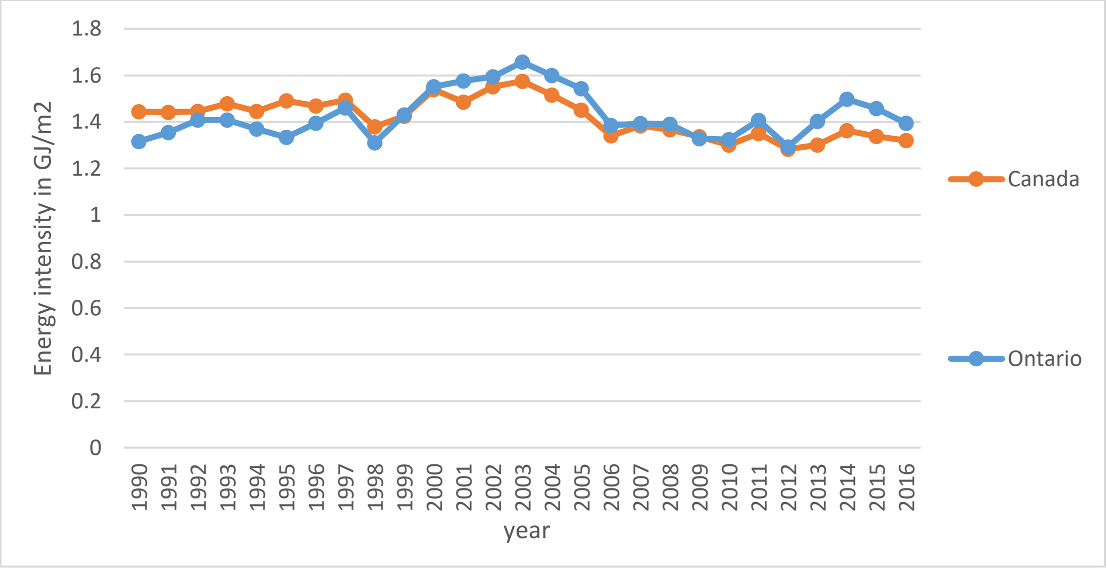


Figure 4.5 Energy consumption intensity of commercial and institutional industries in Canada and Ontario, 1990-2016.

Source: Data retrieved from Natural Resources of Canada: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm)

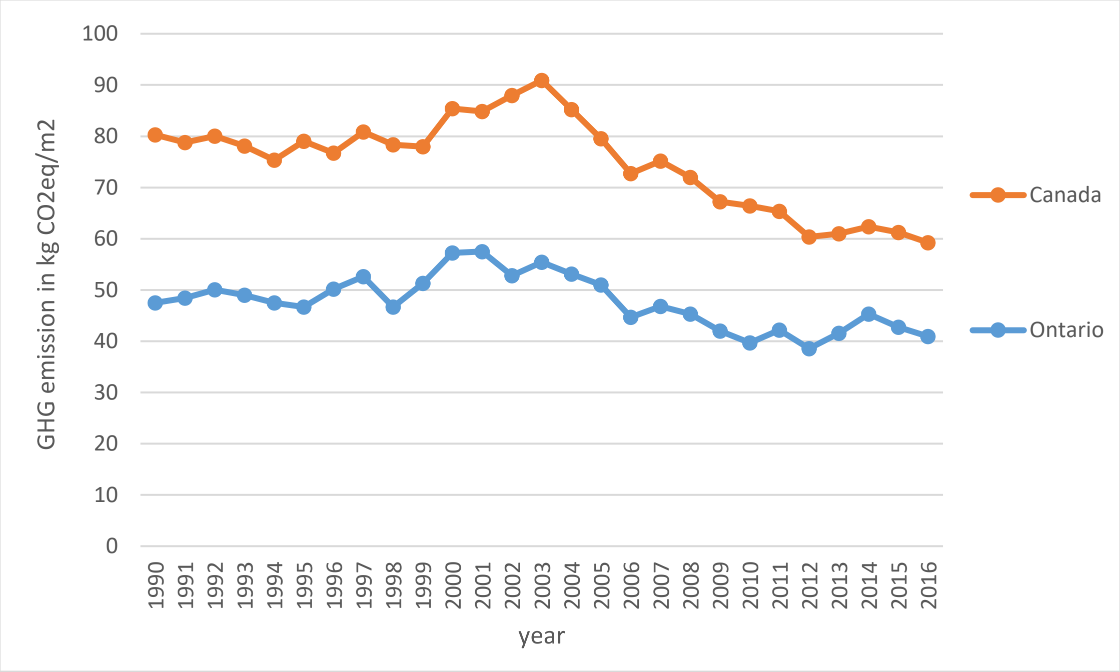


Figure 4.6 GHG emission intensity by commercial and institutional industries in Canada and Ontario, 1990-2016.

Source: Data retrieved from Natural Resources Canada: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm)

Note: The Ontario data did not include emissions from electricity production activities.

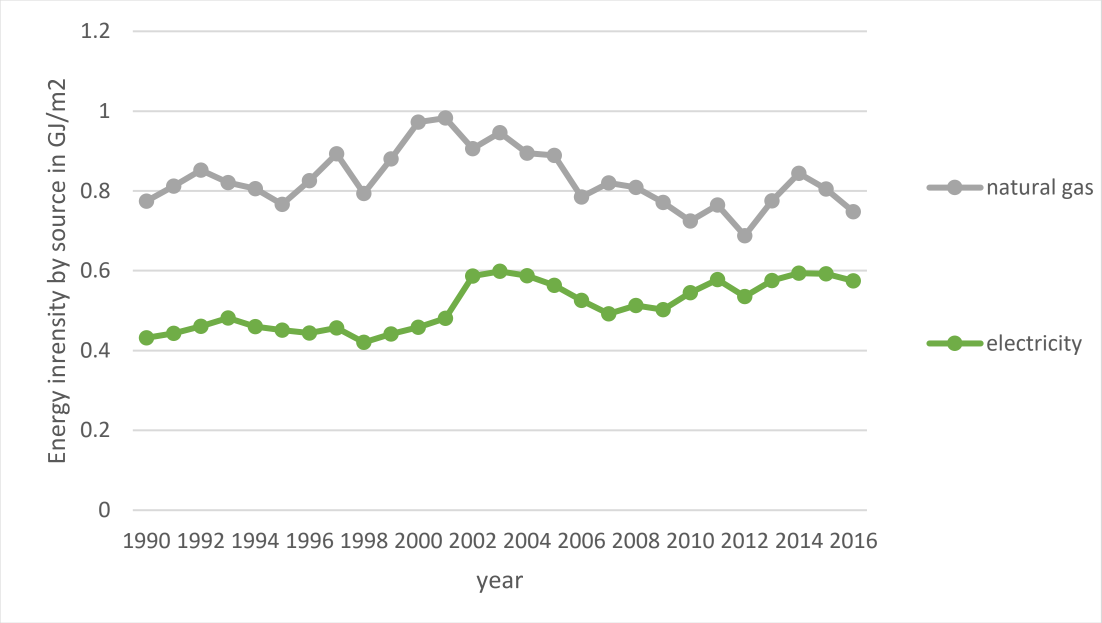


Figure 4.7 Energy intensity by source for commercial and institutional industries in Ontario, 1990-2016.

Source: Data retrieved from Natural Resources of Canada: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm

Electricity and natural gas were the two main secondary energy sources which accounted for more than 90% of the total secondary energy consumption in Ontario's commercial and institutional industries (buildings were the main consumers).

### 4.1.2 University Annual Energy Consumption/Emission Trends

There were two main types of buildings where the tenants were previously located. The first one was commercial/institutional buildings and the second one was campus buildings. Here the two types of buildings were separated and compared with similar commercial buildings or campus buildings, in order to see the level of energy/emission performance of these old tenants' buildings.

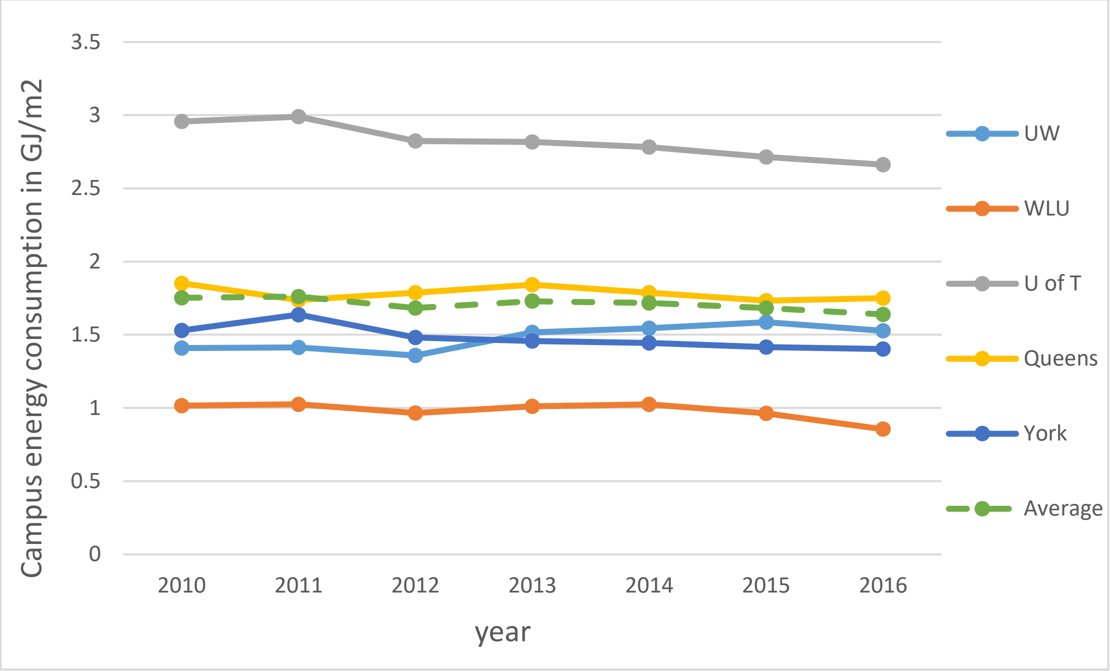


Figure 4.8 Energy consumption by university, GJ/m2, 2010-2016.

Data were obtained to study the trends of campus energy intensity as well as the level of energy consumption of the two universities who had employees/students move into the new building. The average value is shown as the green dashed line. Various data sources were used to make the graph. The University of Waterloo and University of Toronto data were mainly from their annual sustainability reports, while other university data were primarily from the reports of their energy department staff through emails. The data sources were not selected randomly. The sustainability reports for each campus were the primary sources of the data. However, when some of the campuses did not have their data listed in the reports, their employees were contacted through emails as a secondary method obtaining the data. Data in the figure were not normalized for weather conditions.

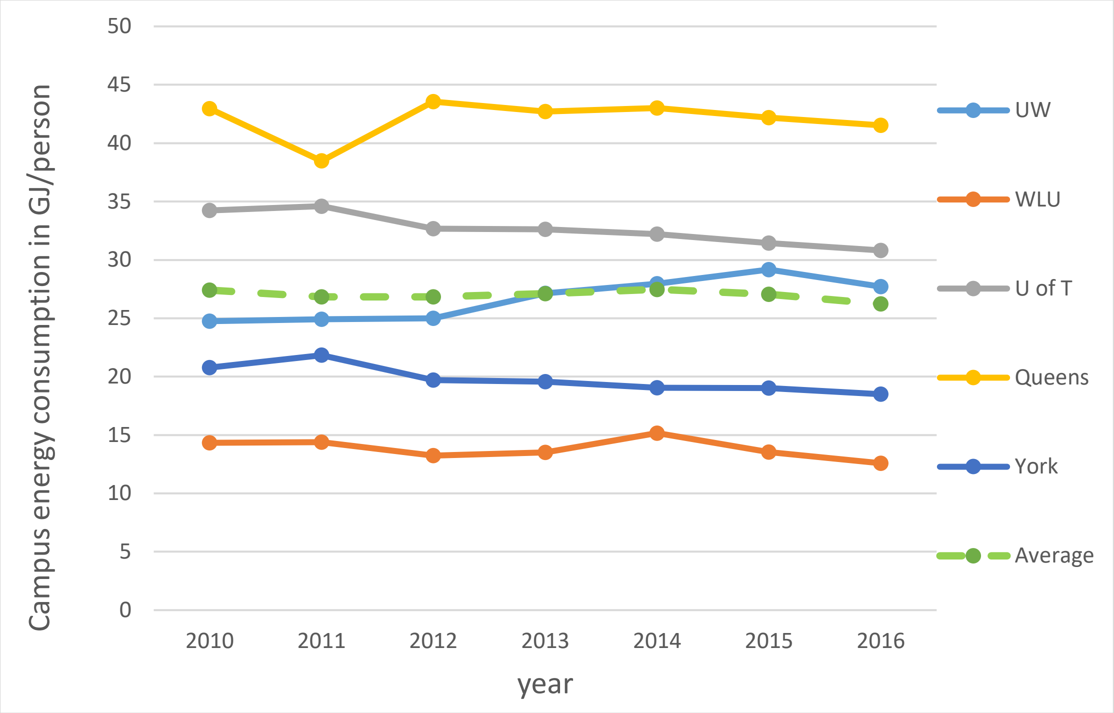


Figure 4.9 Energy consumption by university, GJ/person, 2010-2016

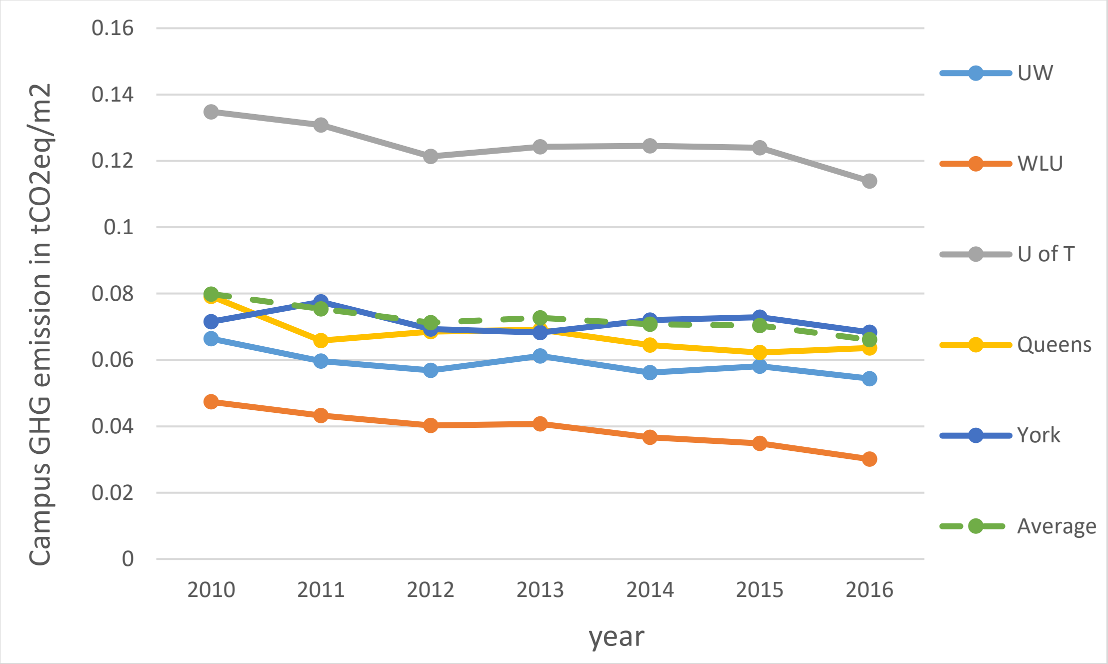


Figure 4.10 GHG emissions by university, tCO2 equivalent (eq)/m2, 2010-2016

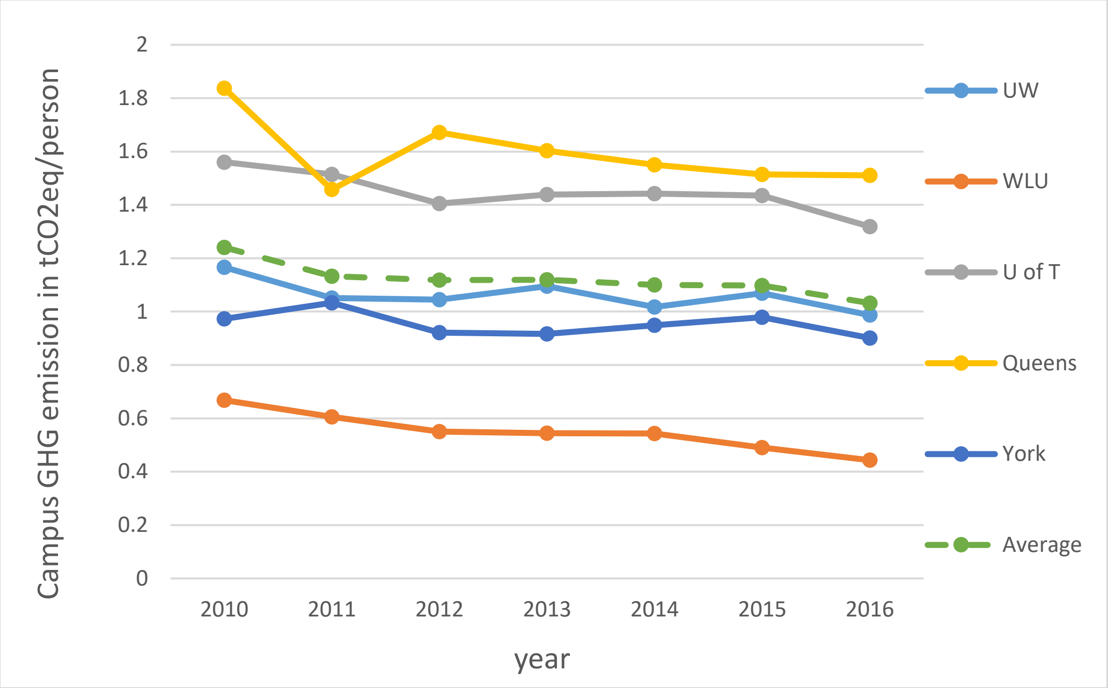


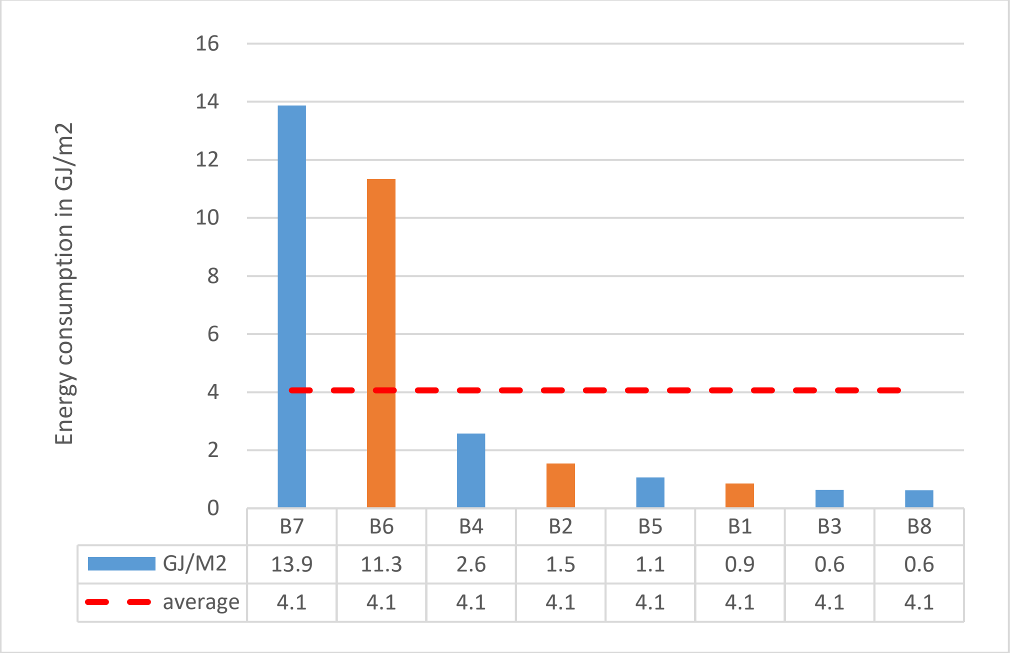
Figure 4.11 GHG emissions by university, tCO2eq /person, 2010-2016

The differences can be due to the size and number of energy-intensive buildings on the campuses. Another influential factor was the campus population. Since energy consumption and emissions were mainly due to the operation of buildings (e.g. heating, cooling, and lighting), the more people sharing building use, the smaller the energy consumption and emission numbers are per person. For example, the University of Toronto has the biggest campus among these six universities, and has the largest engineering/laboratory buildings. Consequently, it has the largest energy consumption/m2 and largest emission/m2 as shown in figure 4.8 and 4.10. However, U of T also has the largest population among these campuses, so the energy/person and emission/person ratios are not the largest.

University of Waterloo and Wilfrid Laurier University had relatively low energy consumption and emissions during the past decade with values below the average of the six comparison universities. It then follows that the two universities that our tenants were from were better than average in energy efficiency when compared to other campuses.

### 4.1.3 Institutional and Commercial Tenants Buildings Analysis

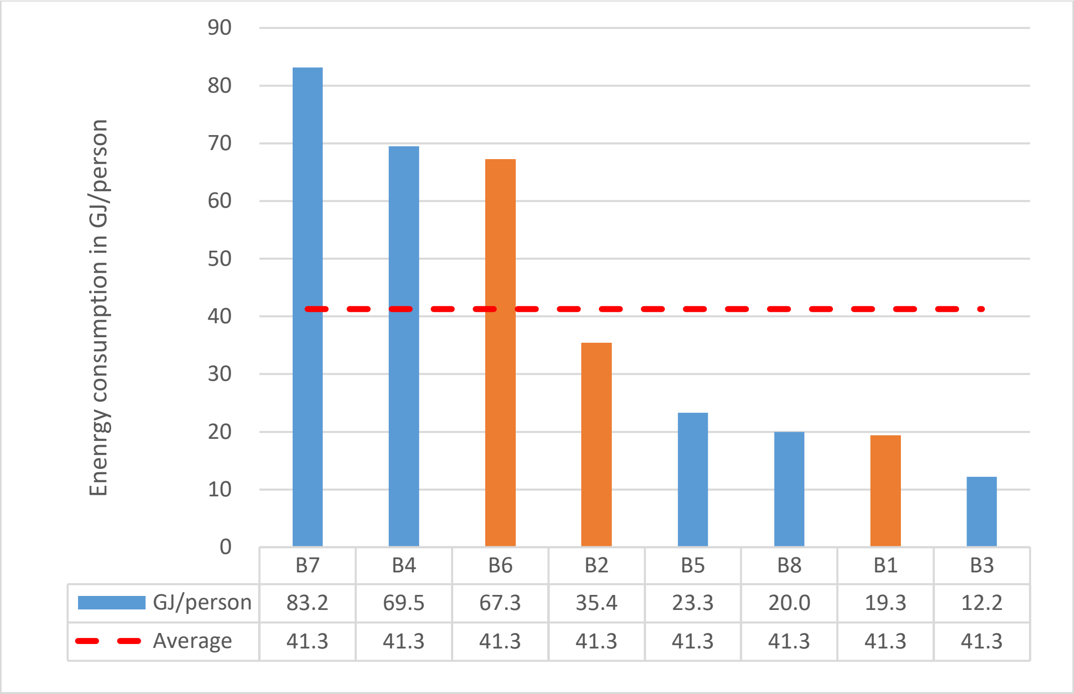
The energy/emission performance of eight institutional and commercial buildings from the R&T Park were studied, along with the tenants' previous buildings.



| | B7 | B6 | B4 | B2 | B5 | B1 | B3 | B8 |
|---|---|---|---|---|---|---|---|---|
| GJ/M2 | 13.9 | 11.3 | 2.6 | 1.5 | 1.1 | 0.9 | 0.6 | 0.6 |
| average | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 |

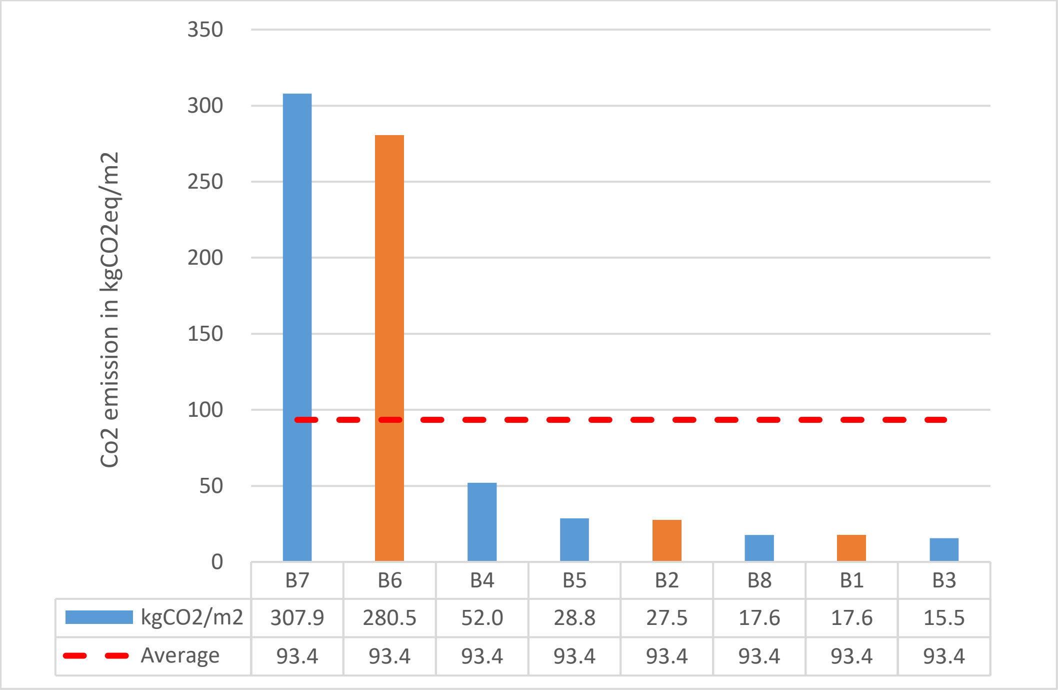
Figure 4.12 R&T Park commercial building energy consumption 2016, GJ/m2.

The annual total energy consumption of eight buildings was used for the analysis, including both the electricity consumption and the natural gas consumption of the buildings. The buildings are referred to as B1 to B8 (according to the alphabetical order of their names). The bars in the graph from left to right were ordered by the values from highest to lowest energy intensity. The three bars marked in orange indicate the three previous office buildings of the tenants. The red line in the graph follows the average energy consumption in GJ/m2 for the eight buildings in 2016.



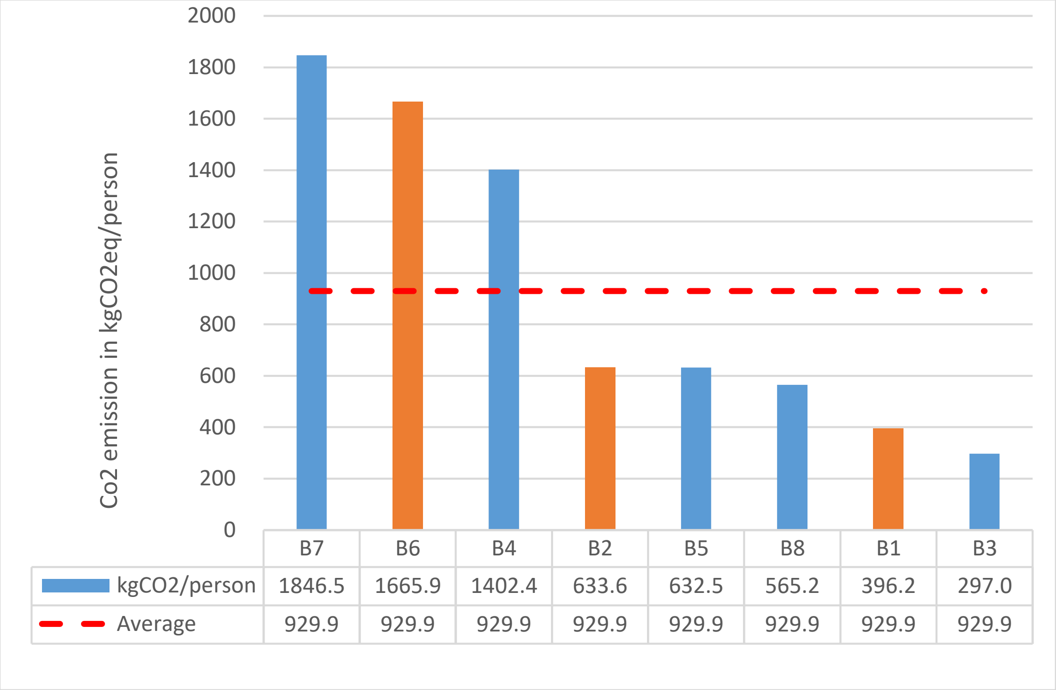
| | B7 | B4 | B6 | B2 | B5 | B8 | B1 | B3 |
|---|---|---|---|---|---|---|---|---|
| GJ/person | 83.2 | 69.5 | 67.3 | 35.4 | 23.3 | 20.0 | 19.3 | 12.2 |
| Average | 41.3 | 41.3 | 41.3 | 41.3 | 41.3 | 41.3 | 41.3 | 41.3 |

Figure 4.13 R&T Park commercial building energy consumption 2016, GJ/person



| | B7 | B6 | B4 | B5 | B2 | B8 | B1 | B3 |
|---|---|---|---|---|---|---|---|---|
| kgCO2/m2 | 307.9 | 280.5 | 52.0 | 28.8 | 27.5 | 17.6 | 17.6 | 15.5 |
| Average | 93.4 | 93.4 | 93.4 | 93.4 | 93.4 | 93.4 | 93.4 | 93.4 |

Figure 4.14 R&T Park commercial building CO2 emissions 2016, kgCO2eq/m2



|  | B7 | B6 | B4 | B2 | B5 | B8 | B1 | B3 |
|---|---|---|---|---|---|---|---|---|
| kgCO2/person | 1846.5 | 1665.9 | 1402.4 | 633.6 | 632.5 | 565.2 | 396.2 | 297.0 |
| Average | 929.9 | 929.9 | 929.9 | 929.9 | 929.9 | 929.9 | 929.9 | 929.9 |

Figure 4.15 R&T Park commercial building CO2 emissions 2016, kgCO2eq/person

The above figures show that the three previous tenant buildings included two buildings with low values in energy and emission intensity and one building which was over double the intensity. The building average energy intensity was raised by high energy use labs located in buildings B6 and B7, although the tenants who were to move only occupied office space. Meanwhile, they were sharing the building with some energy-intensive chemistry and physics labs. When the tenant in B6 moved into the new building, they did not carry energy-intensive equipment with them, so it may not be proper to use these large values to present their actual energy/emissions in that building. To set up a more accurate pre-occupancy energy/emission baseline for the case study building, the data of the energy intensive lab building should be excluded. In addition, because 2017 was the last year before they moved into the new building, using 2017 data for the office buildings may give more accurate values for the baselines. After excluding the laboratory buildings (e.g. B6 and B7), the B8 building is the only office building which did not report the 2017 energy/emission data within the R&T Park.

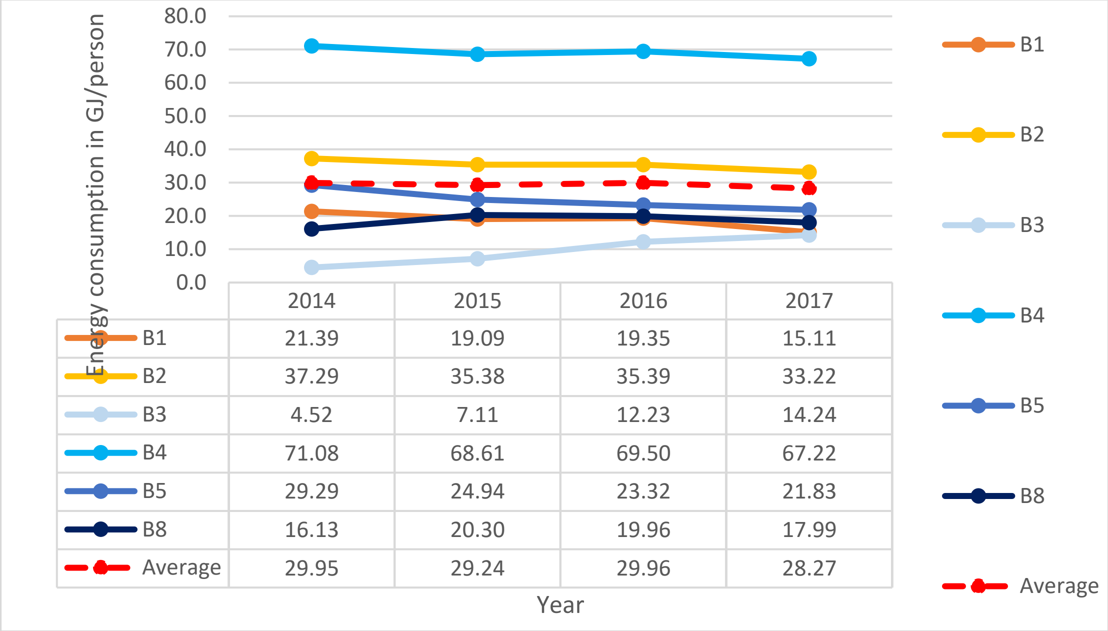
The annual energy/emissions of office buildings is closely related to the total heating/cooling days of the year (since climate control would comprise the lion’s share of energy use/emission release in an office building, because these buildings do not have energy-intensive labs as on-campus buildings do). In this case, a linear regression was done by using the past years’ energy/emission data of the B8 building with the climate control days (cooling degree days (CDDs) and heating degree days (HDDs)) as reported by the local weather stations in order to estimate the 2017 energy/emissions of the building. Then, the values can be used with the 2017 data of the other buildings to set up the new office building averages in the RT Park. (Details of calculations in Appendix B)

The short-term energy and emission trends of all the selected office buildings (B1 to B8, not including B6 and B7) are as follows:

| | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|
| B1 | 0.95 | 0.85 | 0.86 | 0.67 |
| B2 | 1.62 | 1.53 | 1.53 | 1.44 |
| B3 | 0.24 | 0.37 | 0.64 | 0.74 |
| B4 | 2.64 | 2.55 | 2.58 | 2.49 |
| B5 | 1.33 | 1.13 | 1.06 | 0.99 |
| B8 | 0.50 | 0.63 | 0.62 | 0.56 |
| Average | 1.21 | 1.18 | 1.22 | 1.15 |

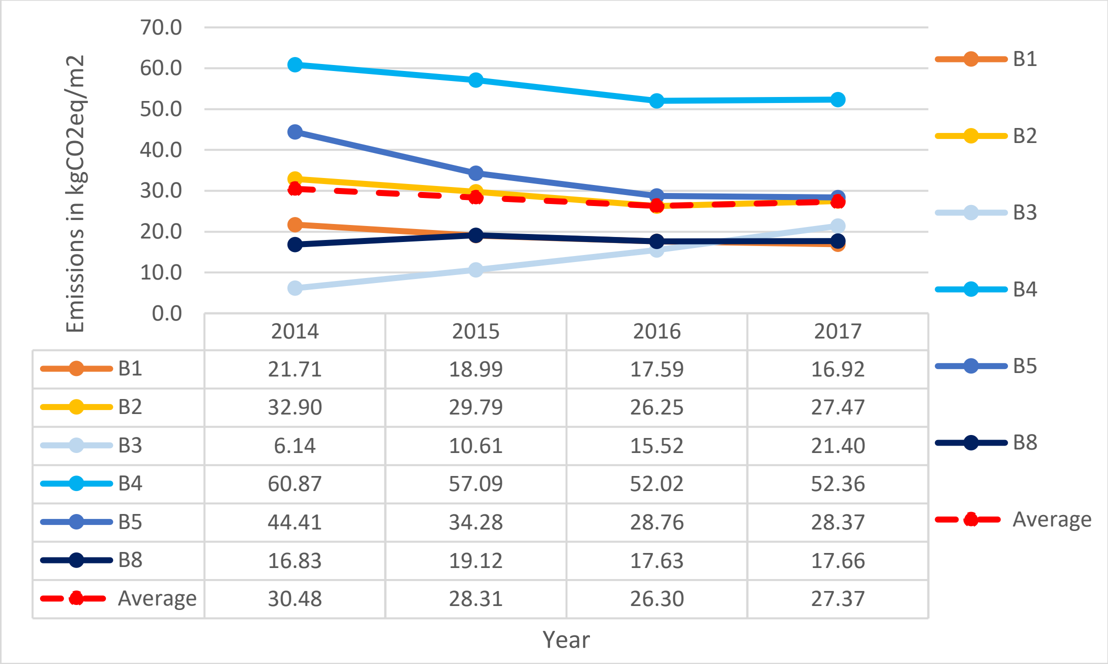
Figure 4.16 R&T Park office buildings energy consumption 2014-2017, GJ/m2.

Note: the estimated 2017 data for B8 was used and the B6, B7 buildings were excluded in this and next three graphs. The tenants’ previous buildings are represented in warm colors (red, orange, yellow) while other office buildings are represented in cool colors (blue, purple). The red dashed line indicates the short-term trend of the annual averages.



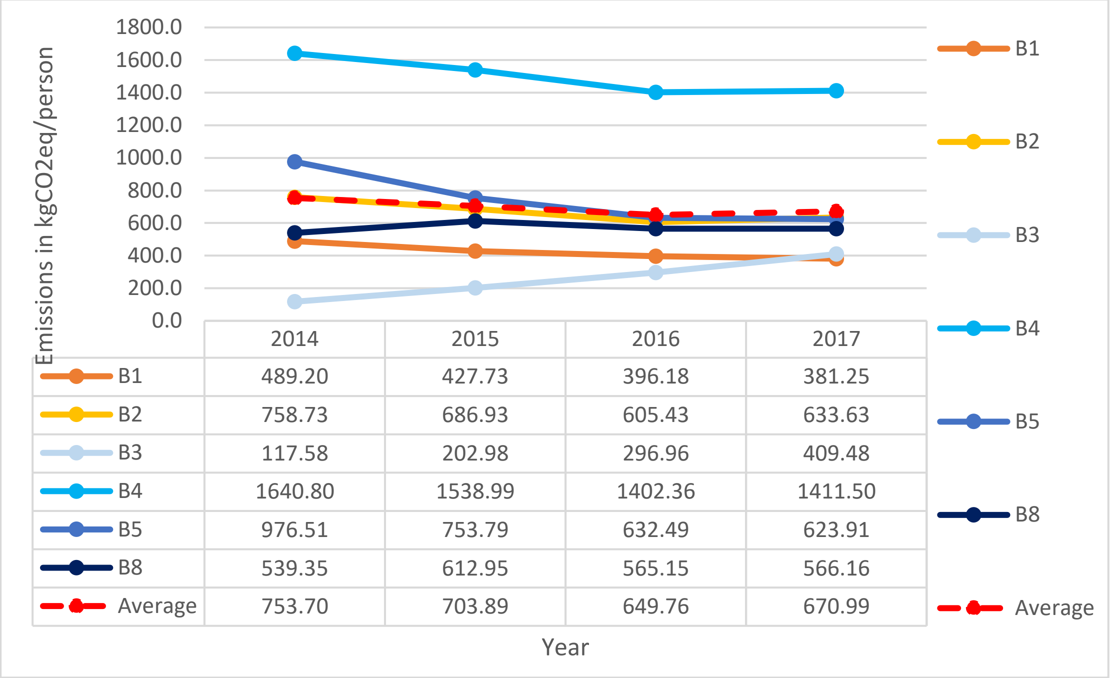
| | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|
| B1 | 21.39 | 19.09 | 19.35 | 15.11 |
| B2 | 37.29 | 35.38 | 35.39 | 33.22 |
| B3 | 4.52 | 7.11 | 12.23 | 14.24 |
| B4 | 71.08 | 68.61 | 69.50 | 67.22 |
| B5 | 29.29 | 24.94 | 23.32 | 21.83 |
| B8 | 16.13 | 20.30 | 19.96 | 17.99 |
| Average | 29.95 | 29.24 | 29.96 | 28.27 |

Figure 4.17 R&T Park office buildings energy consumption 2014-2017, GJ/person.



| | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|
| B1 | 21.71 | 18.99 | 17.59 | 16.92 |
| B2 | 32.90 | 29.79 | 26.25 | 27.47 |
| B3 | 6.14 | 10.61 | 15.52 | 21.40 |
| B4 | 60.87 | 57.09 | 52.02 | 52.36 |
| B5 | 44.41 | 34.28 | 28.76 | 28.37 |
| B8 | 16.83 | 19.12 | 17.63 | 17.66 |
| Average | 30.48 | 28.31 | 26.30 | 27.37 |

Figure 4.18 R&T Park office buildings emissions 2014-2017, kgCO2eq/m2.



| | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|
| B1 | 489.20 | 427.73 | 396.18 | 381.25 |
| B2 | 758.73 | 686.93 | 605.43 | 633.63 |
| B3 | 117.58 | 202.98 | 296.96 | 409.48 |
| B4 | 1640.80 | 1538.99 | 1402.36 | 1411.50 |
| B5 | 976.51 | 753.79 | 632.49 | 623.91 |
| B8 | 539.35 | 612.95 | 565.15 | 566.16 |
| Average | 753.70 | 703.89 | 649.76 | 670.99 |

Figure 4.19 R&T Park office buildings emissions 2014-2017, kgCO2eq/person.

The four figures above show that the two tenants from B1 and B2 tended to decrease their energy consumption and GHG emissions over the past years. In future research, when the tenants' energy consumption and emission data are available after they have moved into the new building, their energy/emission reduction achieved should be values arrived at after subtracting the previous years' deceasing trend values in order to show the effectiveness of the new building. However, the decreases were very slight, and the trend was only made from four years of data. This decreasing trend may therefore not be appropriate for calculation in the analysis later.

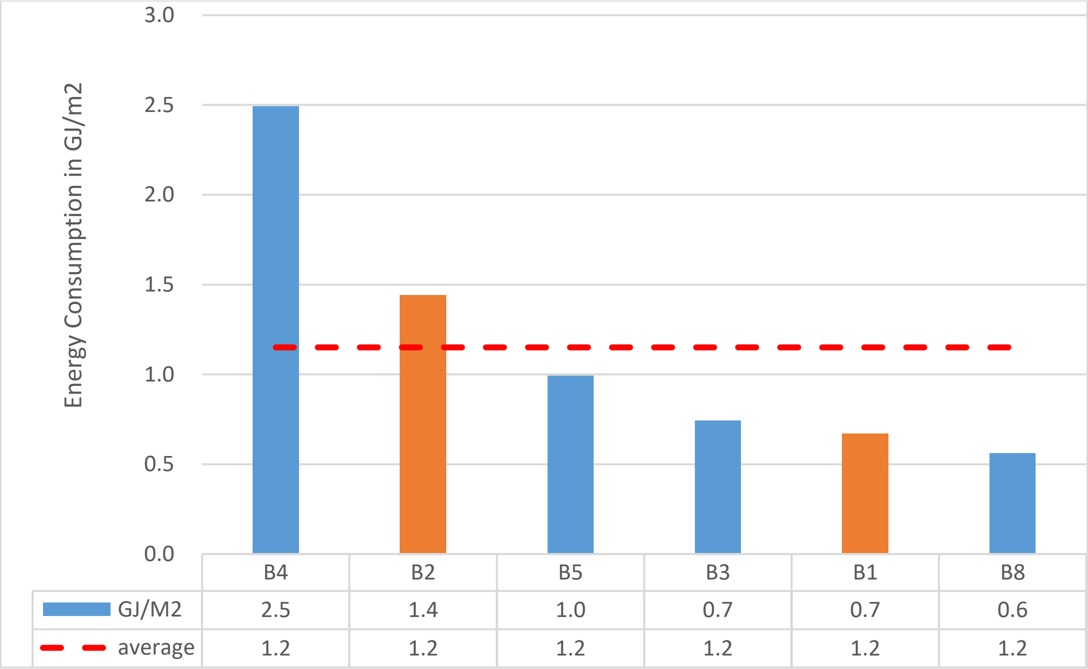


Figure 4.20 R&T Park office buildings energy consumption 2017, GJ/m2.

Note: Estimated 2017 energy consumption data for the B8 building was used in the graph and the two laboratory buildings are excluded from figure 4.20 to 4.23.

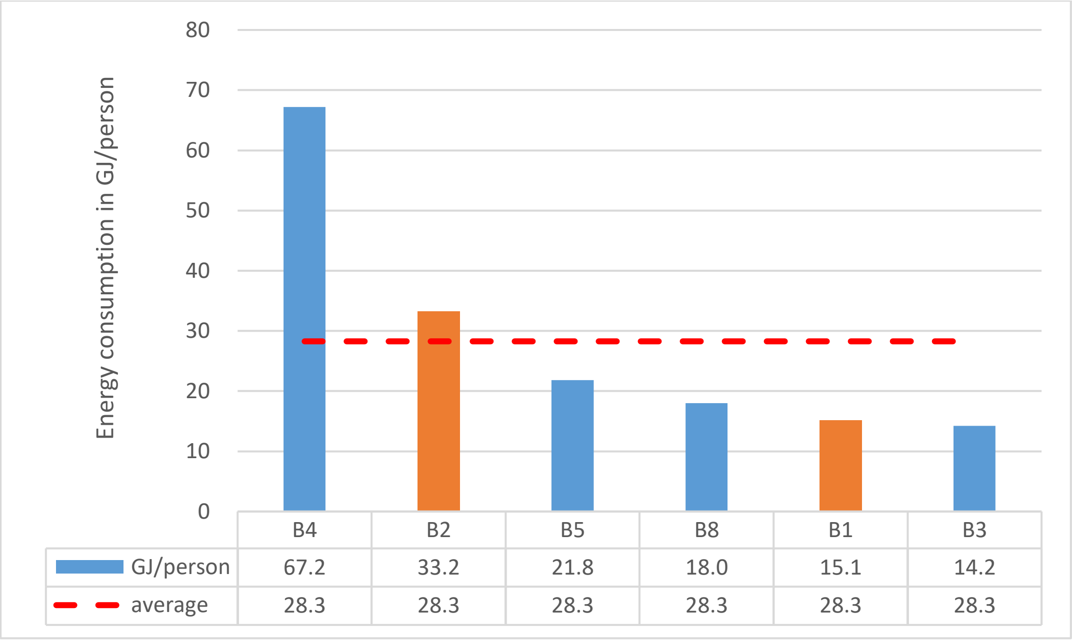


Figure 4.21 R&T Park office buildings energy consumption 2017, GJ/person.

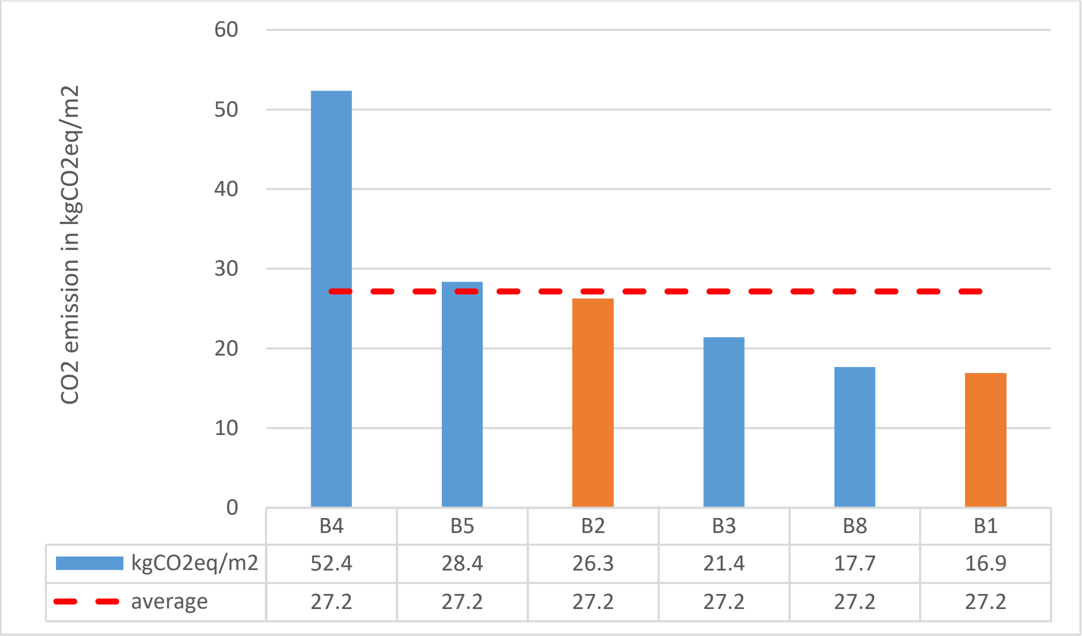


Figure 4.22 R&T Park office buildings emissions 2017, kg CO2eq/m2.

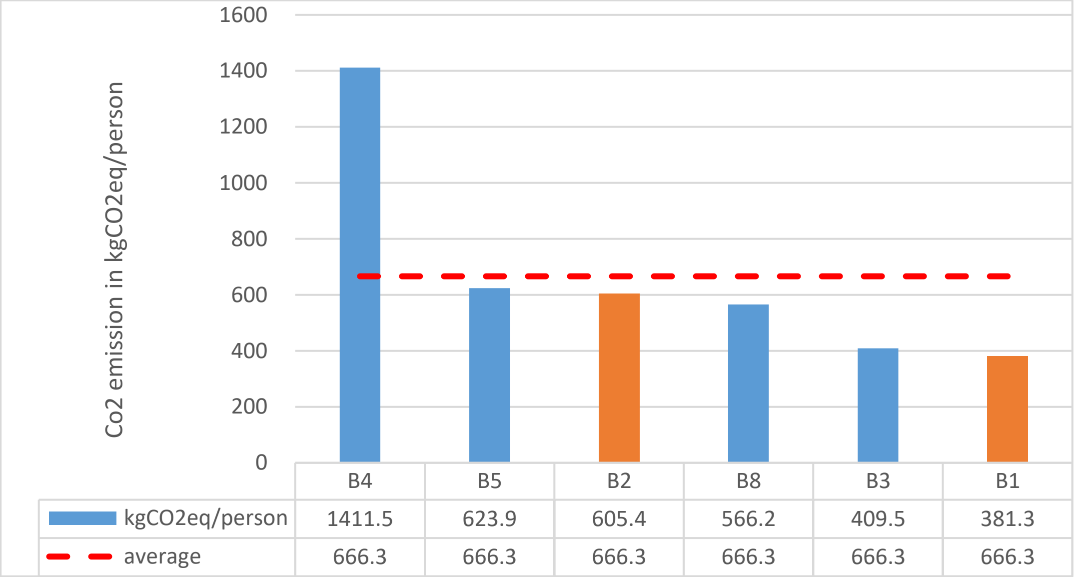
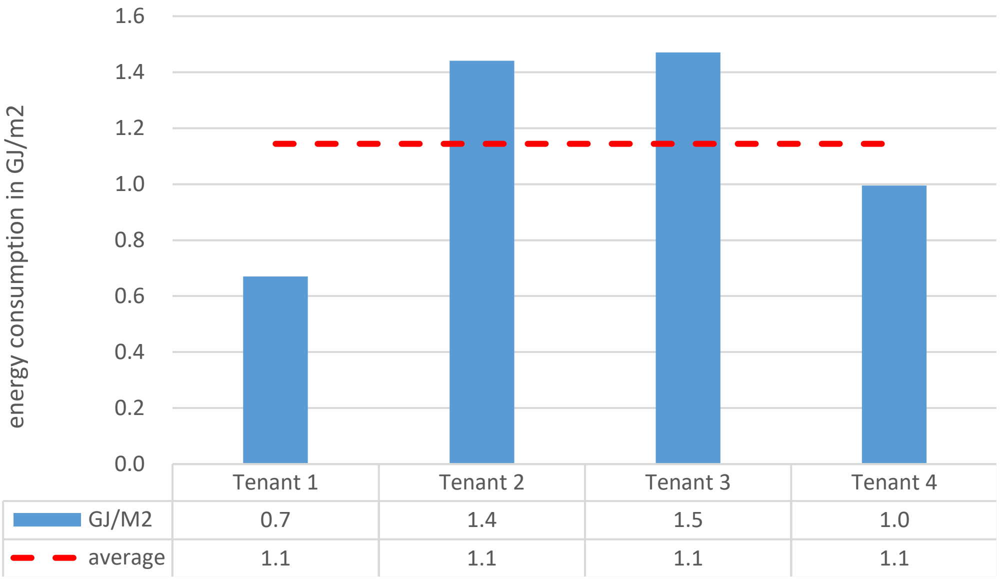


Figure 4.23 R&T Park office buildings emissions 2017, kg CO2eq/person.

The previous office buildings of the two tenants exhibited relatively low energy consumption and emission values when compared to other buildings in the R&T Park. We noticed that the tenants' previous office buildings showed similar energy consumption to the campus buildings, albeit with lower emission values. This can be a product of the higher natural gas usage in campuses within the energy-intensive labs.

***Setting up the baselines***

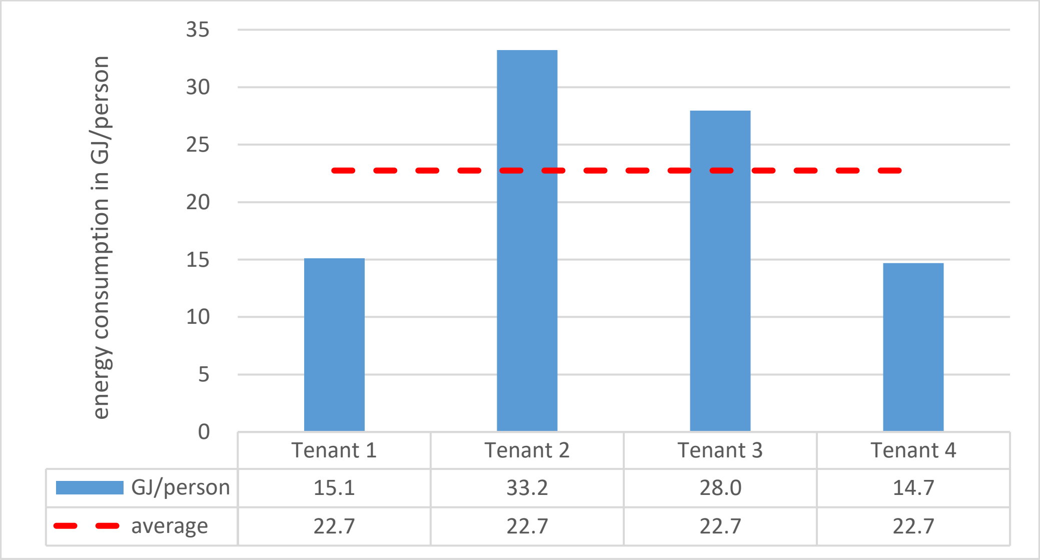
In this section, the building energy/emission baselines calculated from the previous tenants' buildings are displayed.



| | Tenant 1 | Tenant 2 | Tenant 3 | Tenant 4 |
|---|---|---|---|---|
| ▬ GJ/M2 | 0.7 | 1.4 | 1.5 | 1.0 |
| ╍ average | 1.1 | 1.1 | 1.1 | 1.1 |

Figure 4.24 Previous buildings energy consumption baseline 2017, GJ/m2.

The four tenants were renamed Tenant 1 to 4 according to alphabetical order of their real names. The commercial/institutional buildings and campuses were combined to build up the baseline value. The two commercial/institutional buildings were from the R&T Park (Tenants 1 and 2) and the two campuses were the University of Waterloo main campus and the Wilfrid Laurier University main campus (Tenants 3 and 4). The data were from the year 2017, the year prior to the employee move into the new building in 2018. The average value of the four tenants in their previous buildings was used as the baseline energy consumption value for the new building.



| | Tenant 1 | Tenant 2 | Tenant 3 | Tenant 4 |
|---|---|---|---|---|
| ▬ GJ/person | 15.1 | 33.2 | 28.0 | 14.7 |
| ╍ average | 22.7 | 22.7 | 22.7 | 22.7 |

Figure 4.25 Previous buildings energy consumption baseline 2017, GJ/person

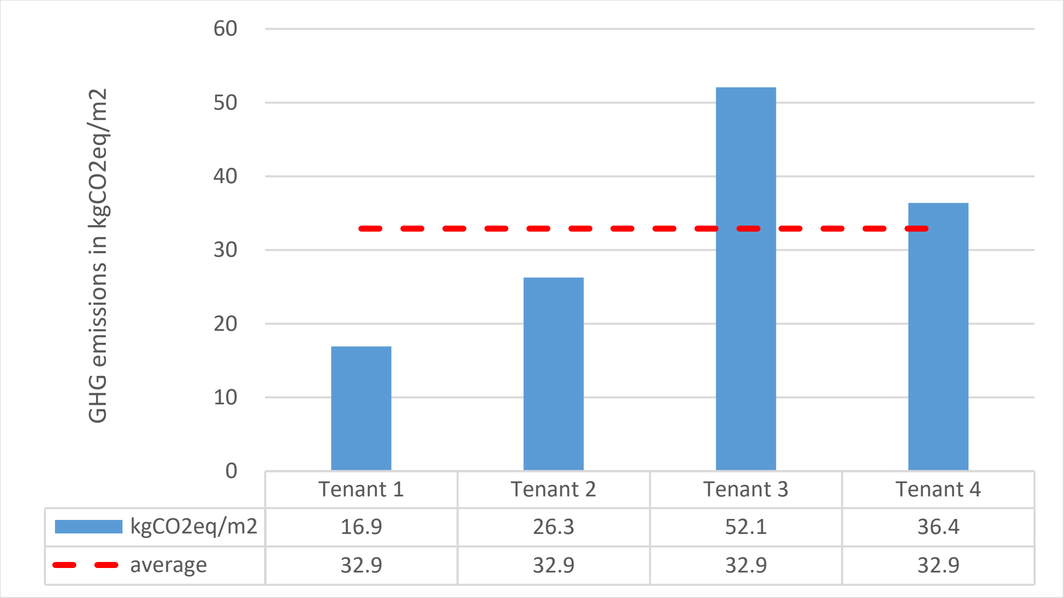


Figure 4.26 Previous buildings emission baseline 2017, kgCO2eq/m2.

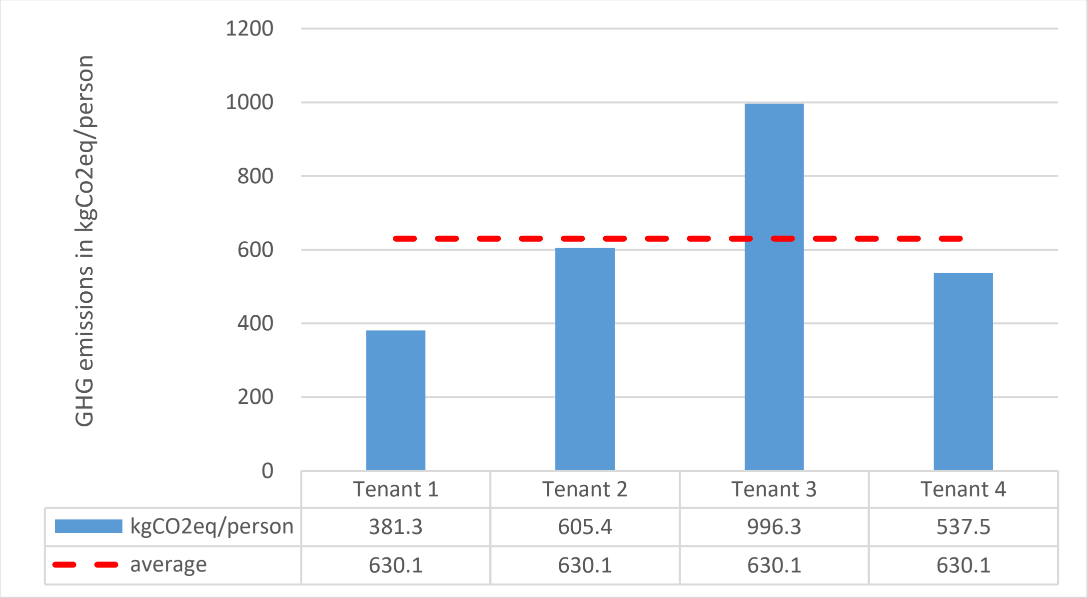


Figure 4.27 Previous buildings emission baseline 2017, kgCO2eq/person.

All the values from the four figures above show the baselines from the previous tenants' buildings, however, each of the tenants occupied a different amount of space after moving into the new building. Consequently, the average value may not be accurate for the estimation. In the following section, a weighted average of energy/emission values was calculated to then be used for comparison with the actual operational data of Evovl1 once the data are available.

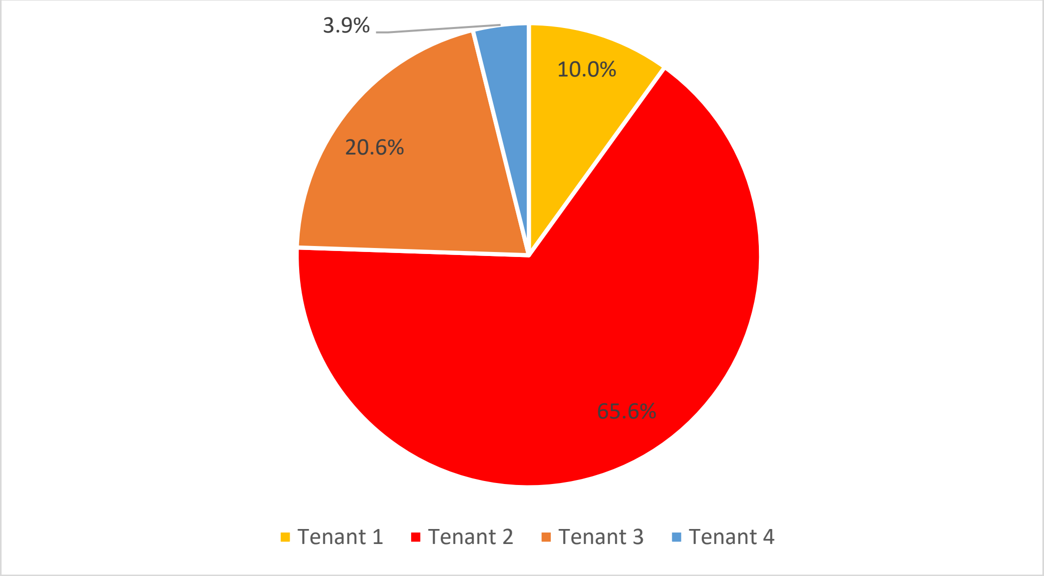


Figure 4.28 The share of occupied space by each tenant in the case study building.

Note: The figure only includes the four tenants with available data. There are seven tenants in the building and the details of the space that they occupy can be seen in Appendix C.

The figure shows that each of the tenants occupied different amounts of space in the new building. In this case, a weighted average (weighted by amount of space occupied in the new building) can be a better estimation for the energy/emission baselines among the previous tenant's buildings.

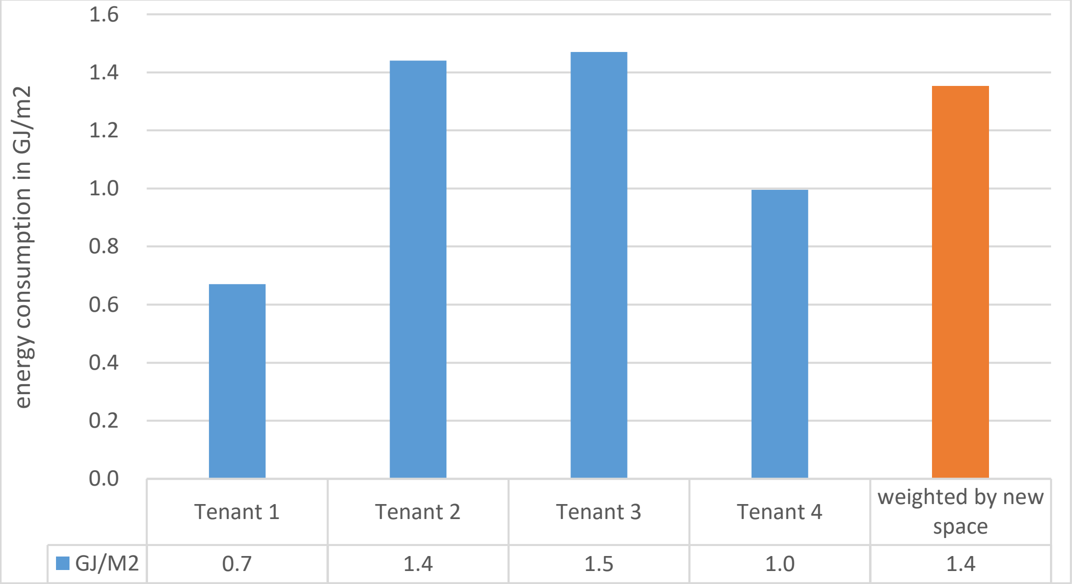


Figure 4.29 Energy consumption baseline values for previous tenants' buildings 2017, GJ/m2.

The orange bar is added here as the weighted value for the energy consumption in GJ/m2. The value was highly affected by tenants 2 and 3 who accounted for larger percentages of space in the new building than the other tenants. The final value for the average weighted energy consumption of the tenants' previous buildings was estimated at 1.4 GJ/m2 annually.

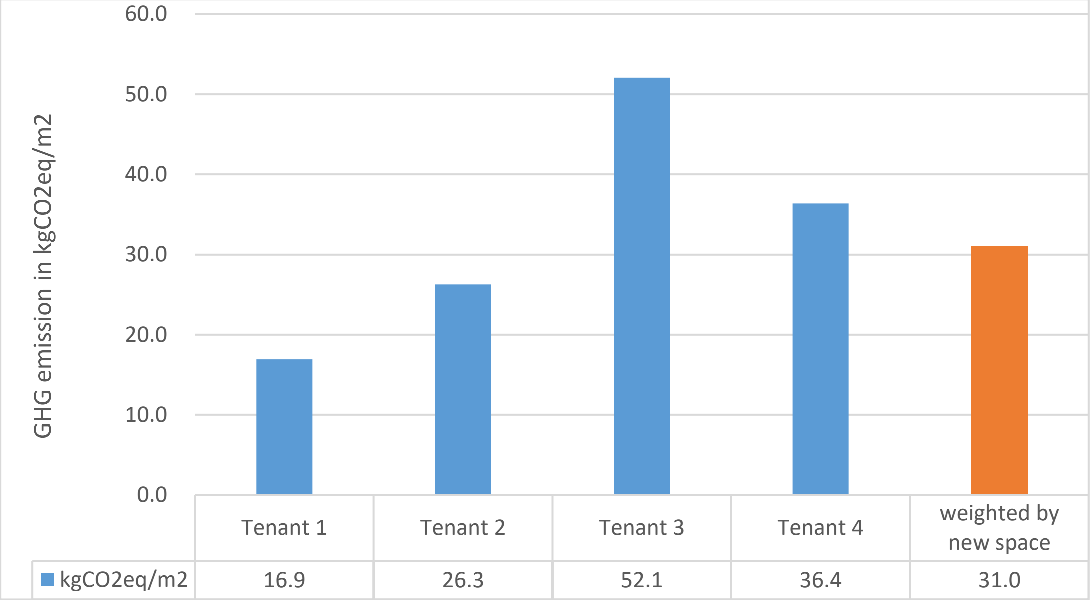


Figure 4.30 GHG emission baseline values for previous tenants' buildings 2017, kgCO2/m2.

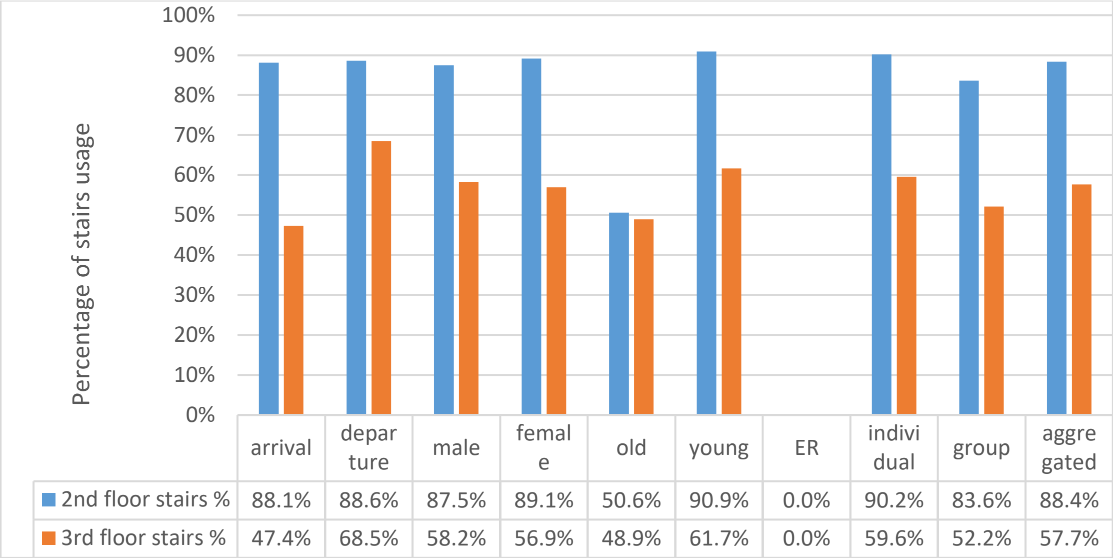
The orange bar is added again here as the weighted value for the energy consumption in kgCO2eq/m2. The value was again highly affected by tenants 2 and 3 who accounted for larger percentages of space in the new building than other tenants. The final value of the GHG emissions in the tenants' previous buildings was estimated at 31 kgCO2/m2 annually.

The weighted values were calculated based on the different amounts of space in the new zero-carbon building occupied by different tenants. Information was not available as to the exact number of people working daily for each tenant in the building, so the weighted values per person were not calculated.

## 4.2 Behavior Analysis

### 4.2.1 Pre-occupancy Elevator and Stair Usage

This section presents the elevator and stair usage in previous tenants' buildings.



| | arrival | departure | male | female | old | young | ER | individual | group | aggregated |
|---|---|---|---|---|---|---|---|---|---|---|
| 🟦 2nd floor stairs % | 88.1% | 88.6% | 87.5% | 89.1% | 50.6% | 90.9% | 0.0% | 90.2% | 83.6% | 88.4% |
| 🟧 3rd floor stairs % | 47.4% | 68.5% | 58.2% | 56.9% | 48.9% | 61.7% | 0.0% | 59.6% | 52.2% | 57.7% |

Figure 4.31 The aggregated pre-occupancy stair usage.

The Y-axis indicates the percentage of people using stairs counted in a specific category during the observations, and the X-axis indicates the different categories used in collecting the elevator and stair usage data.

The data were collected from four buildings where the tenants were located previously: the Environment 3 (EV3) building of the University of Waterloo, the Science Building of Wilfrid Laurier University, and two R&T Park buildings occupied by the case study tenants. In total, 3581 individual counts were included in the observations. The fourth floor data were not included since all the data of the post-occupancy and post-engagement stages were second and third floor data.

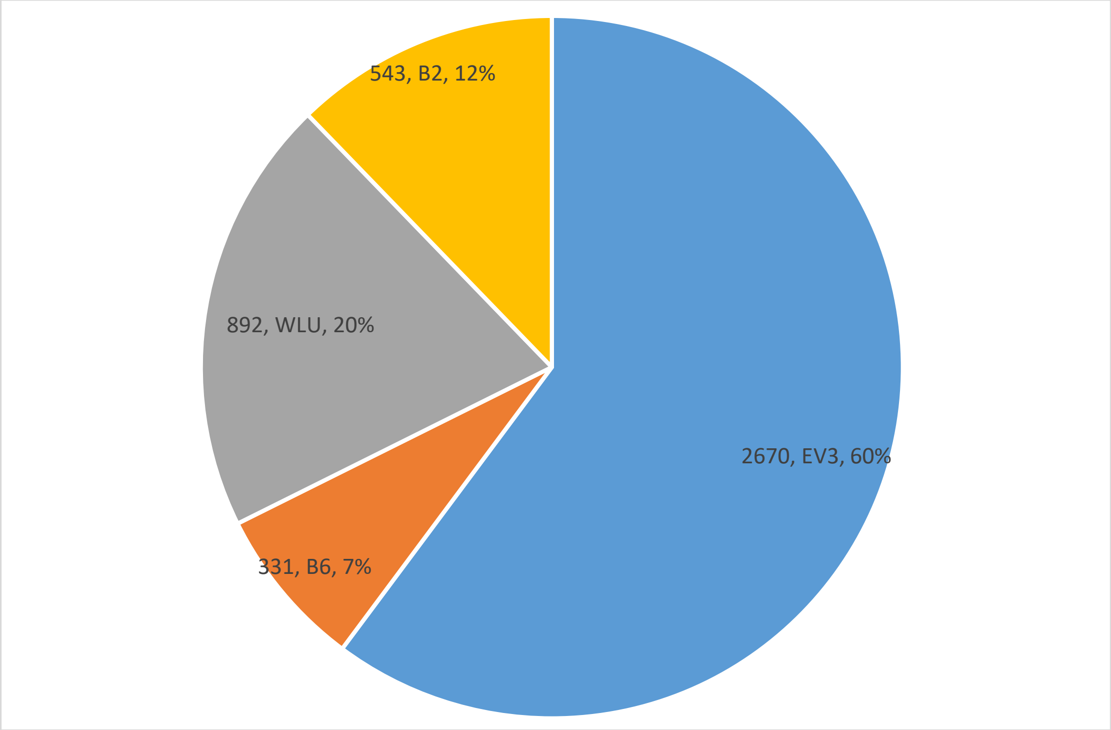


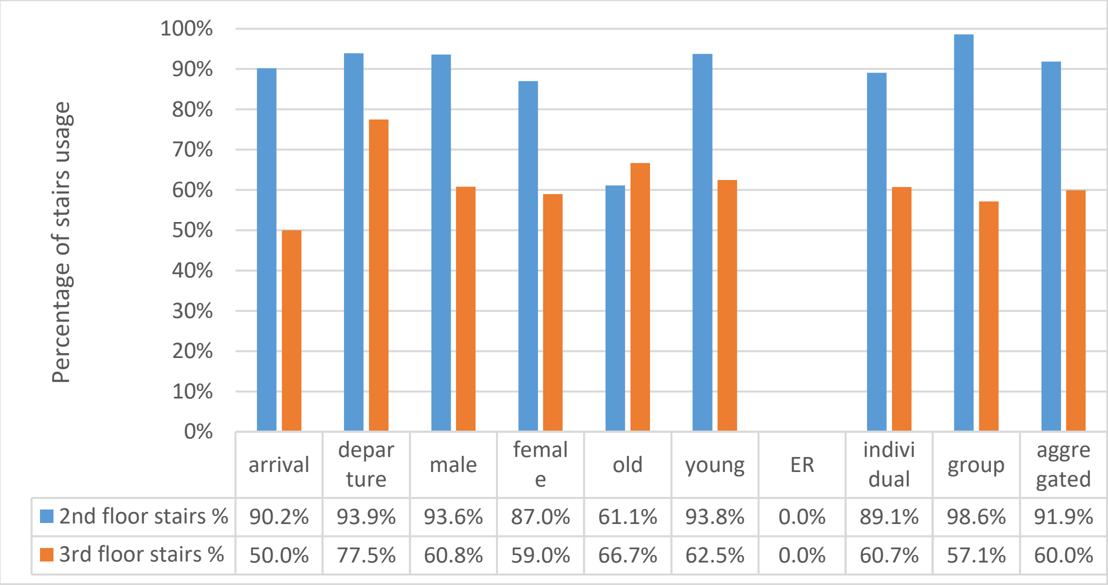
Figure 4.32 Observations of the pre-occupancy elevator and stair usage, by building.

Note: The B2 and B6 Buildings were labelled consistently with figure 4.12.

The data collection time period was 9 hours over three days for each building. The different number of people observed per building was mainly due to the size of each building. The UW and WLU buildings are campus buildings where lectures are held, and therefore very busy during the data collection hours. The fourth floor data are also included in the pie chart.

### 4.2.2 Post-occupancy Elevator and Stair Usage

The post-occupancy stage covered the time period which was after tenants' moved into the new building but before any engagement workshops/activities took place. This section presents the aggregated elevator/stair usage data.



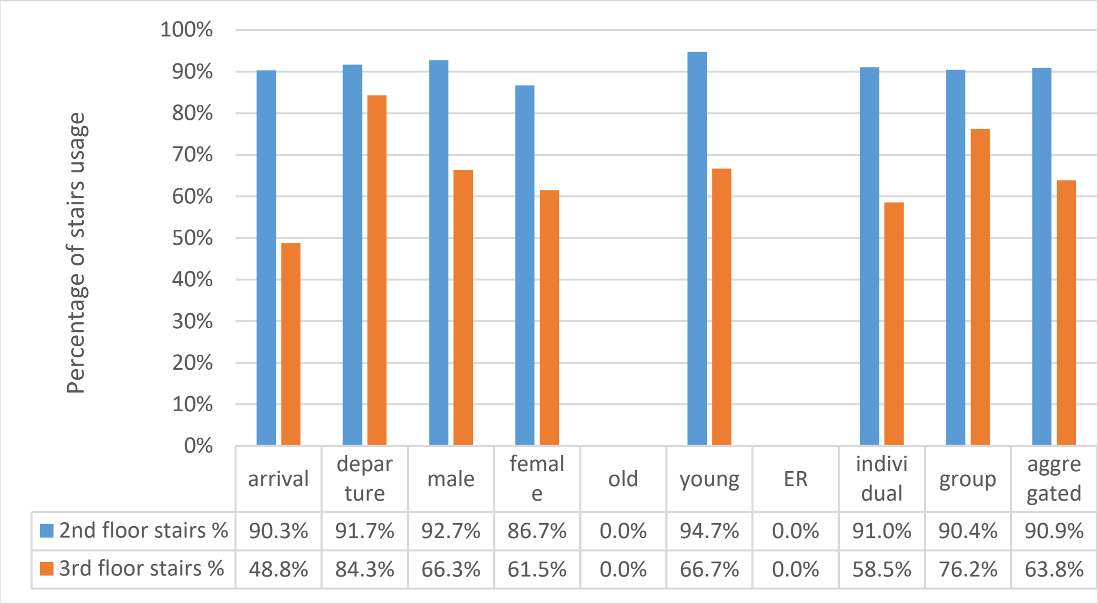
| | arrival | departure | male | female | old | young | ER | individual | group | aggregated |
|---|---|---|---|---|---|---|---|---|---|---|
| 🟦 2nd floor stairs % | 90.2% | 93.9% | 93.6% | 87.0% | 61.1% | 93.8% | 0.0% | 89.1% | 98.6% | 91.9% |
| 🟧 3rd floor stairs % | 50.0% | 77.5% | 60.8% | 59.0% | 66.7% | 62.5% | 0.0% | 60.7% | 57.1% | 60.0% |

Figure 4.33 Aggregated post-occupancy stair usage.

Since the new building is a three-floor building, the data collected from its second and third floors through observations were used. In total, the number of people movements counted was 922 over four days. This number is much smaller than the pre-occupancy observations. The main reasons were: first, the pre-occupancy data were collected from different buildings, included campus buildings with heavy student traffic, so numbers inflated when there were lectures/classes; second, three of the four tenants from the previous four-tenant building where the pre-occupancy data were collected are now located on the ground floor of the new building so they no longer use stairs or elevators.

### 4.2.3 Post-engagement Elevator and Stair Usage

The data collected after engagement workshops (after a single set of observations in two days) and activities are analyzed in this section.



| | arrival | departure | male | female | old | young | ER | individual | group | aggregated |
|---|---|---|---|---|---|---|---|---|---|---|
| 🟦 2nd floor stairs % | 90.3% | 91.7% | 92.7% | 86.7% | 0.0% | 94.7% | 0.0% | 91.0% | 90.4% | 90.9% |
| 🟧 3rd floor stairs % | 48.8% | 84.3% | 66.3% | 61.5% | 0.0% | 66.7% | 0.0% | 58.5% | 76.2% | 63.8% |

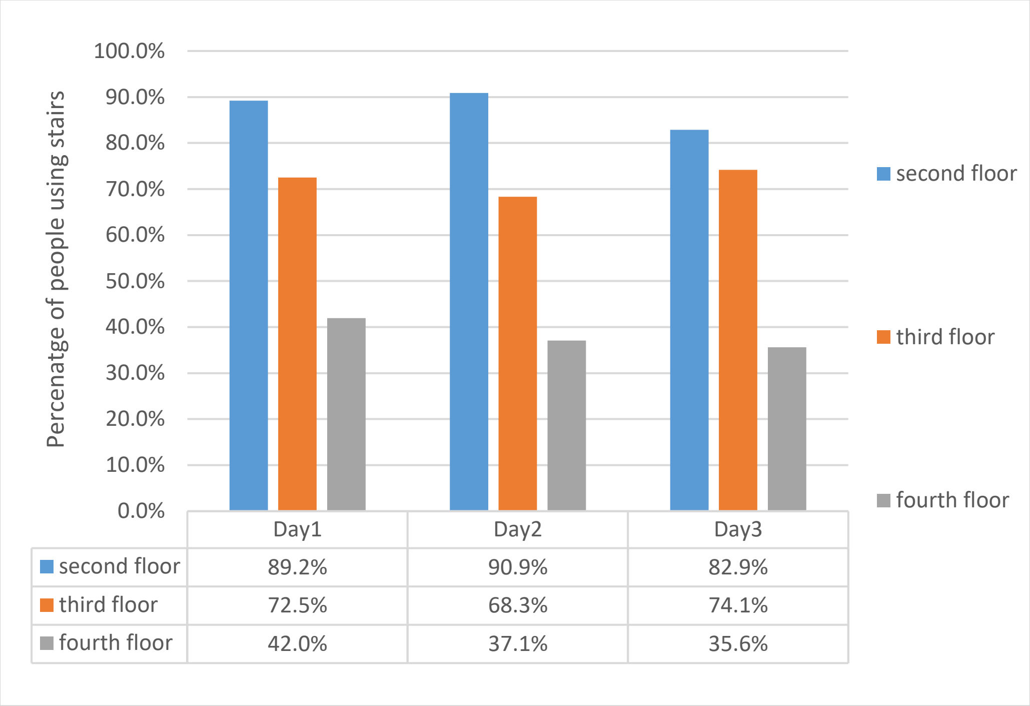
Figure 4.34 Aggregated post-engagement elevator and stairs usage.

Note: The total number of people counted was 407 over two days. This number is smaller than the pre-engagement data collection mainly due to fewer observation days.

### 4.2.4 Potential Influential Factors - Floor Height and Building Design

Moving into the zero-carbon building is associated with two main types of interventions. First, the building has easily accessible central stairs; second, there are regular sustainability engagement workshops.

Among the old buildings, only the EV3 building of the University of Waterloo has a design including a central atrium with accessible stairs similar to the case study building. Other buildings have the main staircase situated away from the central elevators (e.g. the science building in Wilfrid Laurier University) or have only side stairs (some R&T Park buildings). An analysis of stair-use percentages in these buildings was performed in order to see if different building designs influenced stair-use behaviors. Since not enough evidence was gathered to determine whether the different organizations and universities had differing sustainability cultures or stair climbing habits, the tenants were simply treated as individuals working in differently designed buildings.



| | Day1 | Day2 | Day3 |
|---|---|---|---|
| second floor | 89.2% | 90.9% | 82.9% |
| third floor | 72.5% | 68.3% | 74.1% |
| fourth floor | 42.0% | 37.1% | 35.6% |

Figure 4.35 Stair-usage percentages of second, third and fourth floor in a central-stair building.

Tenants were on different floors in their previous buildings before they moved into the new building. From figures 4.31, 4.33 and 4.34, we see that third-floor occupants used stairs less often than the second-floor occupants in most cases. Therefore, the effects of floor height should be studied before the analysis of effects from the different building designs. The central-stair building used in the analysis was the only building that had stair-elevator observations on multiple floors during the pre-occupancy stage, and it was found that people on the higher floors used the stairs significantly less often than people on the lower floors ($p = 7.42E\text{-}06 < 0.05$). In addition, a regression test was done in order to figure out if stairs usage varied by different days of observation. Since no statistical evidence ($P = 0.457 > 0.05$) showed that the stair usage percentages were significantly different from one day to another, it seems reasonable to use any day as representative of the general pattern for people’s behaviors.

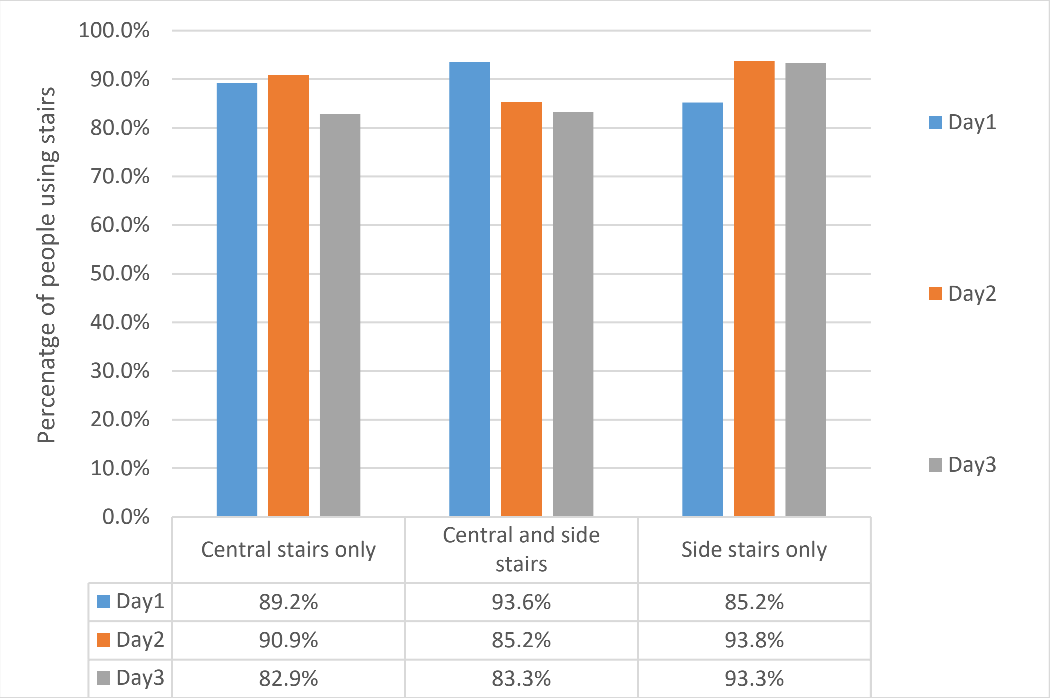


Figure 4.36 Stair-usage percentages for people on the second floor of buildings with different designs.

Data from the three days of observations in the pre-occupancy stage of each of the three buildings were used for the analysis. Since it was the case that floor height affected people's stair usage, only second floor data were used to do the analysis above. After conducting the ANOVA tests, a p value = 0.659 > 0.05 was found for the test, meaning that no significant effect was found among different building designs when studying second-floor stair usage. This result is contradictory to the literature. One possible reason could be that stair usage was affected by convenience. The central stairs of the building that only has central stairs are close to the main entrance and are quite convenient for people to take. On the other hand, the multiple side stairs of the other two buildings are closer to the entrances/parking lot than the central elevators, and again people are encouraged to take the stairs more often. The influence of a central-stair design may have been partially offset by the convenience of multiple side stairs in this case.

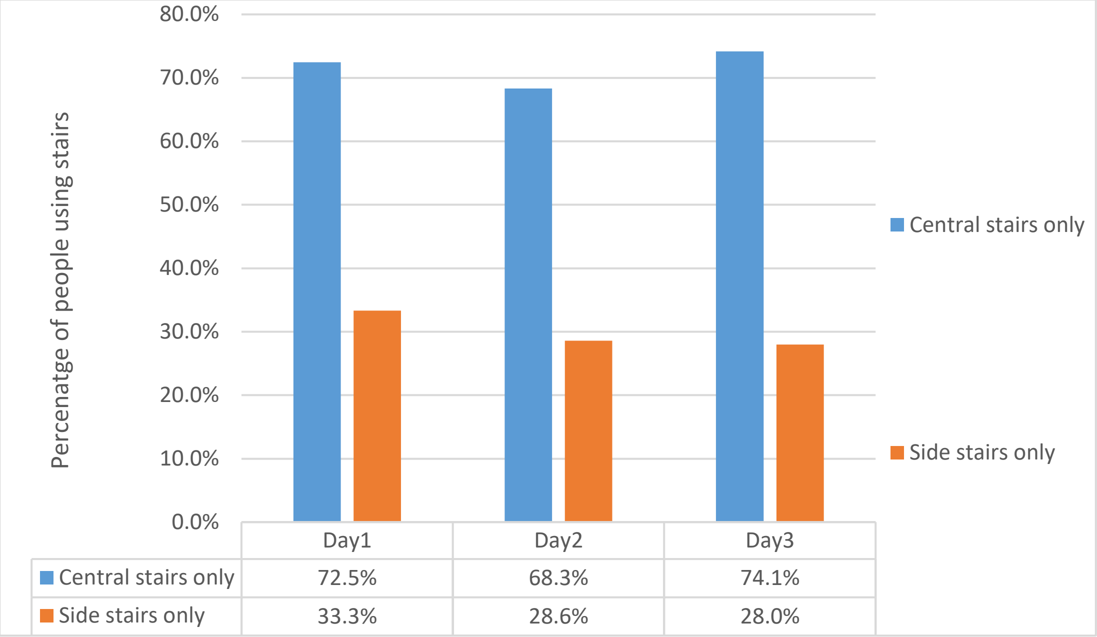


Figure 4.37 Stair-usage percentages for people on the third floor of buildings with different designs.

Building design was found to have a significant effect on third floor stair usage, (ANOVA test, $p = 6.7E\text{-}05 < 0.05$). The reason for the differing results obtained for second and third floor analysis was possibly due to floor height, which clearly had a strong effect on people's elevator-stair choices.

***Elevators required vs elevators by choice***

The number of "ER" ("Elevators Required") subjects, reflected the total number of people in the building who needed elevators as a convenient service tool. However, for the purpose of this research, people who actually had a choice were of far greater interest since the goal here is to study people's sustainable behavior choices. As a result, the "ER" occupants were removed from the total and the remaining occupants were used to compare the stair-usage ratios in different stages again.

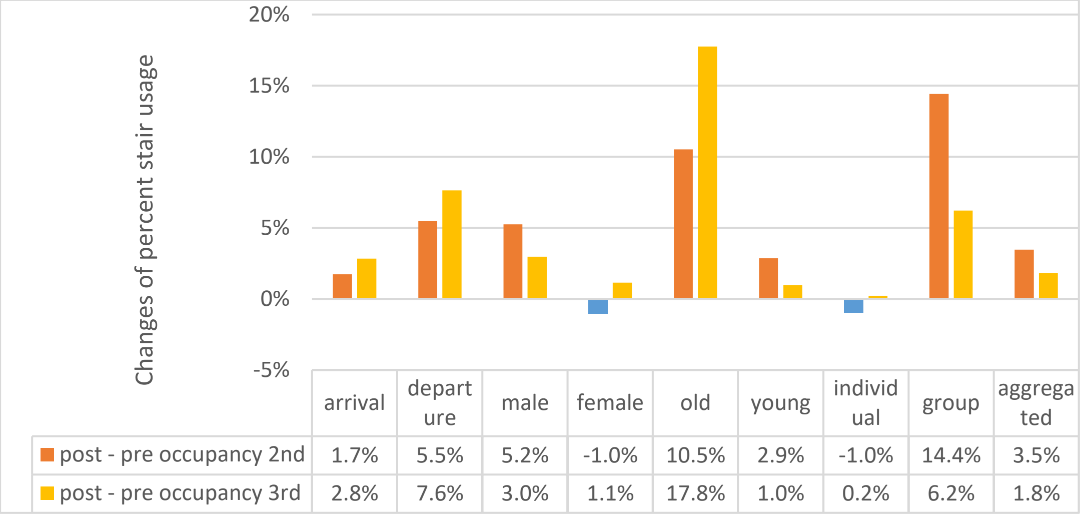
| Research stages | % ER | %EC |
|---|---|---|
| Pre-occupancy | 7.3% | 92.7% |
| Post-occupancy | 12.7% | 87.3% |
| Post-engagement | 12.8% | 87.2% |

Table 4.1 Percentages of "elevators required" people (ER) and "elevators chosen" people (EC) by stage of research.

The table indicates the percentages of ER subjects from observations. These subjects used elevators 100% of the time and were not expected to change their behaviors after interventions, so they were excluded from the following analysis.

### 4.2.5 Aggregated Elevator and Stair Usage Comparison for Different Stages

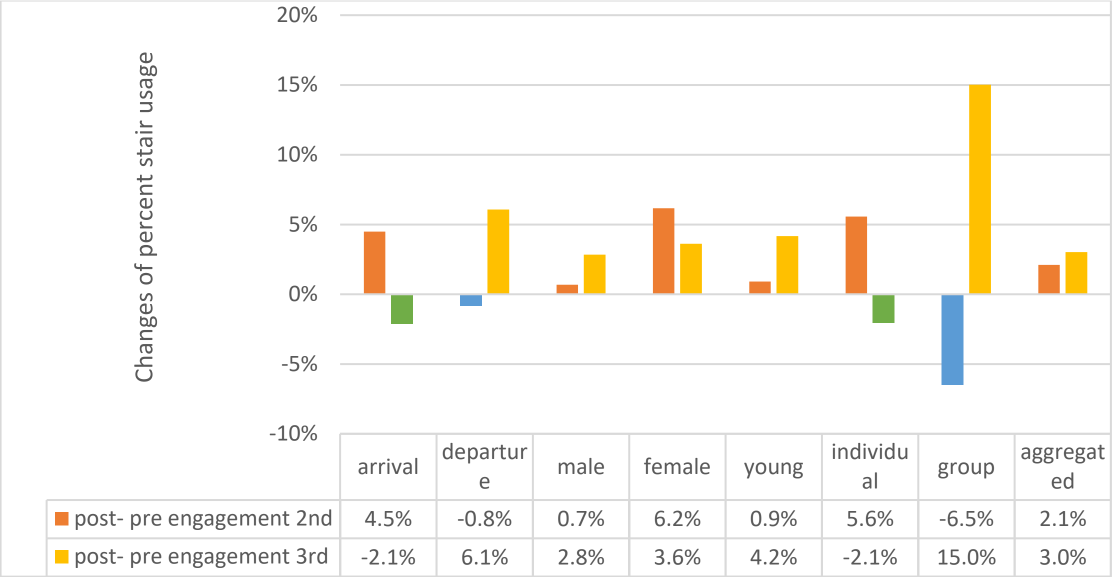
In this part, the changes of stair-usage percentages in different research stages were identified. Since the differences in stair usage based on floor height were identified in the last section, all the fourth-floor data in the pre-occupancy stage were excluded from the analysis. In addition, the "ER" subjects were excluded from the analysis as they were not expected to change their behaviors with interventions.



| | arrival | departure | male | female | old | young | individual | group | aggregated |
|---|---|---|---|---|---|---|---|---|---|
| 🟧 post - pre occupancy 2nd | 1.7% | 5.5% | 5.2% | -1.0% | 10.5% | 2.9% | -1.0% | 14.4% | 3.5% |
| 🟨 post - pre occupancy 3rd | 2.8% | 7.6% | 3.0% | 1.1% | 17.8% | 1.0% | 0.2% | 6.2% | 1.8% |

Figure 4.38 Changes of percent stair usage from the pre-occupancy buildings to post-occupancy stage

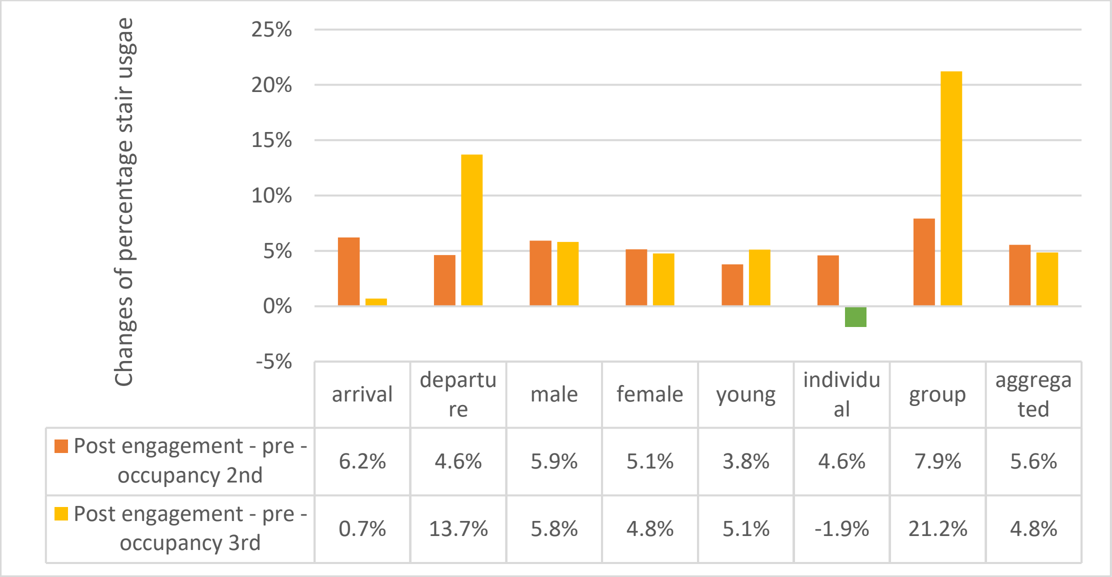
The values were calculated by subtracting the aggregated percentages of stair usage in each of the categories in the previous buildings from the percentages of stair usage in the new building. For all the categories, except for females and individuals, stair usage increased from the pre-occupancy levels, which meant that elevator usage dropped by the same amount. Therefore, this stage exhibits some positive changes of tenants' behaviors on both second and third floors.



| | arrival | departure | male | female | young | individual | group | aggregated |
|---|---|---|---|---|---|---|---|---|
| 🟧 post- pre engagement 2nd | 4.5% | -0.8% | 0.7% | 6.2% | 0.9% | 5.6% | -6.5% | 2.1% |
| 🟨 post- pre engagement 3rd | -2.1% | 6.1% | 2.8% | 3.6% | 4.2% | -2.1% | 15.0% | 3.0% |

Figure 4.39 Changes of percent stair usage from the post-occupancy stage to post-engagement stage.

The aggregated total combining all the data collection dates were used for the comparison in the post-engagement stage. Stair usage for most of the categories increased after the engagement workshops.



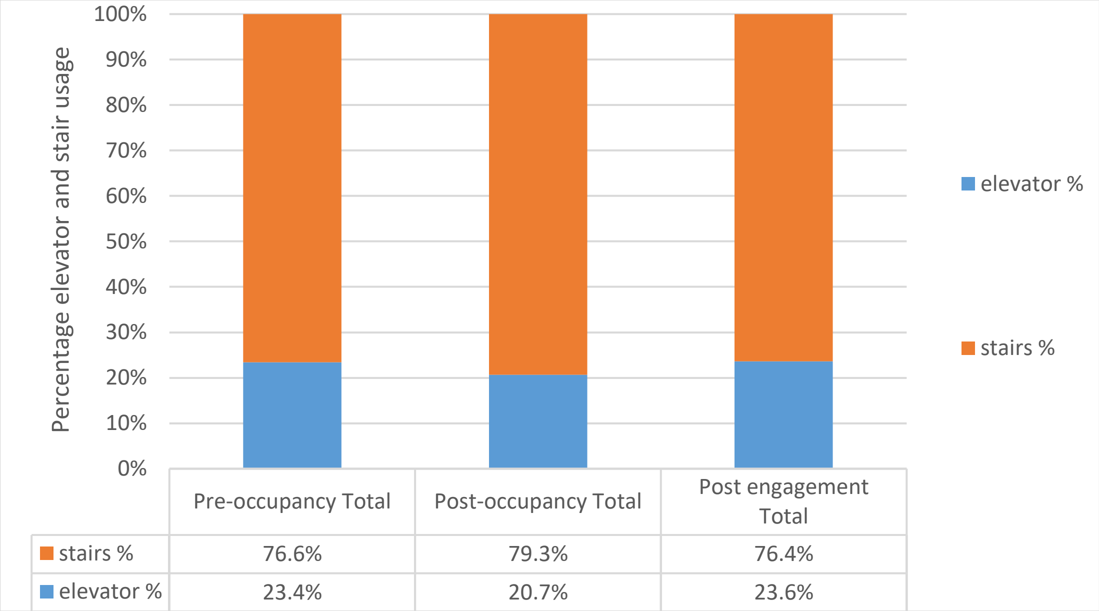
| | arrival | departure | male | female | young | individual | group | aggregated |
|---|---|---|---|---|---|---|---|---|
| 🟧 Post engagement - pre - occupancy 2nd | 6.2% | 4.6% | 5.9% | 5.1% | 3.8% | 4.6% | 7.9% | 5.6% |
| 🟨 Post engagement - pre - occupancy 3rd | 0.7% | 13.7% | 5.8% | 4.8% | 5.1% | -1.9% | 21.2% | 4.8% |

Figure 4.40 Changes of percent stair usage from the pre-occupancy stage to post-engagement stages.

The aggregated total combining all the data collection dates were used again for the comparison in the post-engagement stage. Most categories show increased stair usage. Combing the results from the three figures, we can see that both building design and engagement workshops contributed to people’s positive behavior changes.

Also noticeable from the three figures above is that stair usage increased for most of the categories of occupants after moving into the new building. Overall, we can say that the new building brought positive changes to people’s behaviors. However, due to the inconsistent sample size, further investigations are required to ascertain if the changes are statistically significant.

A chi-square test was used to identify whether the changes in stair usage were significantly different among stages.



|  | Pre-occupancy Total | Post-occupancy Total | Post engagement Total |
|---|---|---|---|
| 🟧 stairs % | 76.6% | 79.3% | 76.4% |
| 🟦 elevator % | 23.4% | 20.7% | 23.6% |

Figure 4.41 Elevator and stair usage percentages (ER subjects and fourth floor EV3 people excluded).

The figure shows the aggregate elevator and stair usage ratios during the three research stages. Combining the aggregated results with the demographic data in figures 4.38, 4.39, and 4.40 in this section, the chi-square tests show that both post-occupancy and post-engagement stages had significantly different stair usage rates than the pre-occupancy stage. (post-occupancy $\chi 2 = 83.3 > 16.9$, df=9, $p = 0.05$ and post-engagement $\chi 2= 452.1 > 16.9$, df=9, $p = 0.05$. The chi-square tests compared the data in each of the demographic categories). Thus, the research indicates that in both the post-occupancy and post-engagement stages, people’s stair usage increased significantly.

Based on the results above, it is clear that the engagement interventions were effective in changing people’s behaviors. Since the culture of sustainability engagement workshops/activities were held monthly, it would be interesting to see how behaviors changed over time in the post-engagement stage in the following analysis.

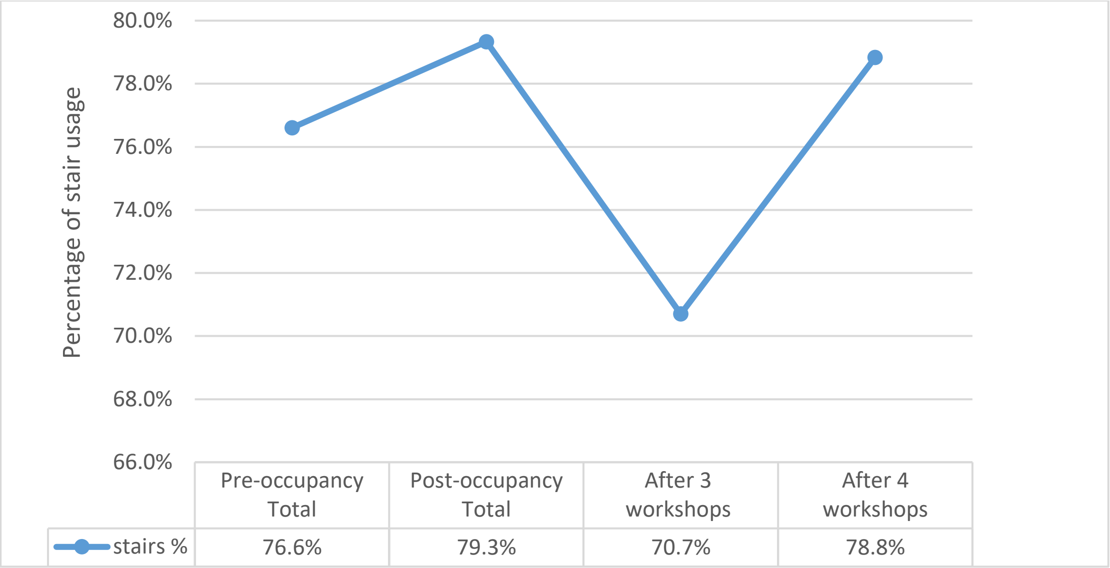
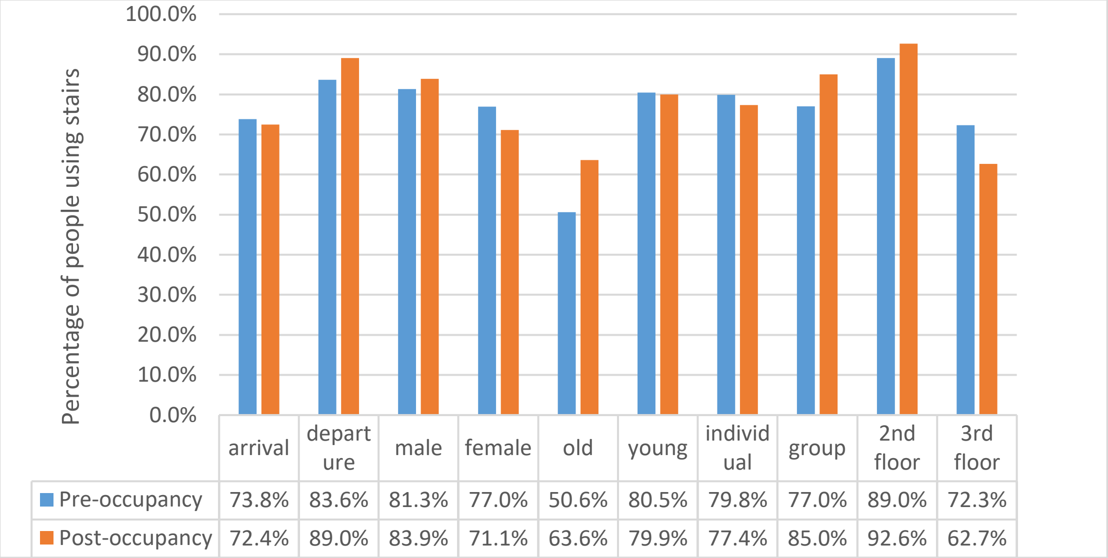


Figure 4.42 Stair usage percentage by period.

Note: The x-axis indicates the different points in time when observations were conducted. Since the R square value was small, the relationship between interventions and stair usage rate was not significant (P= 0.937 > 0.05) after conducting a regression test. One possible reason for this could be the passage of time. People may feel motivated to change behavior when moving into a new energy-efficient building with a sustainable design. This can change people's behaviors initially, however, people's interest may fade away after getting used to the new environment.

### 4.2.6 Separating the Influential Factors

Since significant effects from both building designs and floor height have been seen, a further comparison which separated those influential factors was performed. The EV3 building has both an atrium-central stair design and second and third floors just like the case study building, so it was chosen for direct comparison to the new building.



| | arrival | departure | male | female | old | young | individual | group | 2nd floor | 3rd floor |
|---|---|---|---|---|---|---|---|---|---|---|
| 🟦 Pre-occupancy | 73.8% | 83.6% | 81.3% | 77.0% | 50.6% | 80.5% | 79.8% | 77.0% | 89.0% | 72.3% |
| 🟧 Post-occupancy | 72.4% | 89.0% | 83.9% | 71.1% | 63.6% | 79.9% | 77.4% | 85.0% | 92.6% | 62.7% |

Figure 4.43 Stair usage comparisons.

This figure establishes a comparison of stair-usage percentage in the pre-occupancy stage and the post-occupancy stage of the case study building. An ANOVA test was conducted for the two groups of data, and the result ($P = 0.786 > 0.05$) shows that the stair-usage percentage did not change significantly after people moved into the building. (When conducting the ANOVA test, the “ER” category was excluded as irrelevant. The fourth-floor data of EV3 were also excluded.). By the end of the aggregated data analysis, it was found that the main influential factors for people’s choices in using elevators or stairs can be: first, the position of stairs in the building design; second, the height of floor. Other interventions such as sustainability workshops and activities were not found to have significant effects.

### 4.2.7 Demographic Analysis

Next, the study examined the effects of other factors such as demographic factors on the stair and elevator usage rates. The analysis followed the four main time slots in the previous section (figure 4.42): pre-occupancy, post-occupancy, post-engagement after three workshops/activities, and post-engagement after four workshops/activities

***Age***

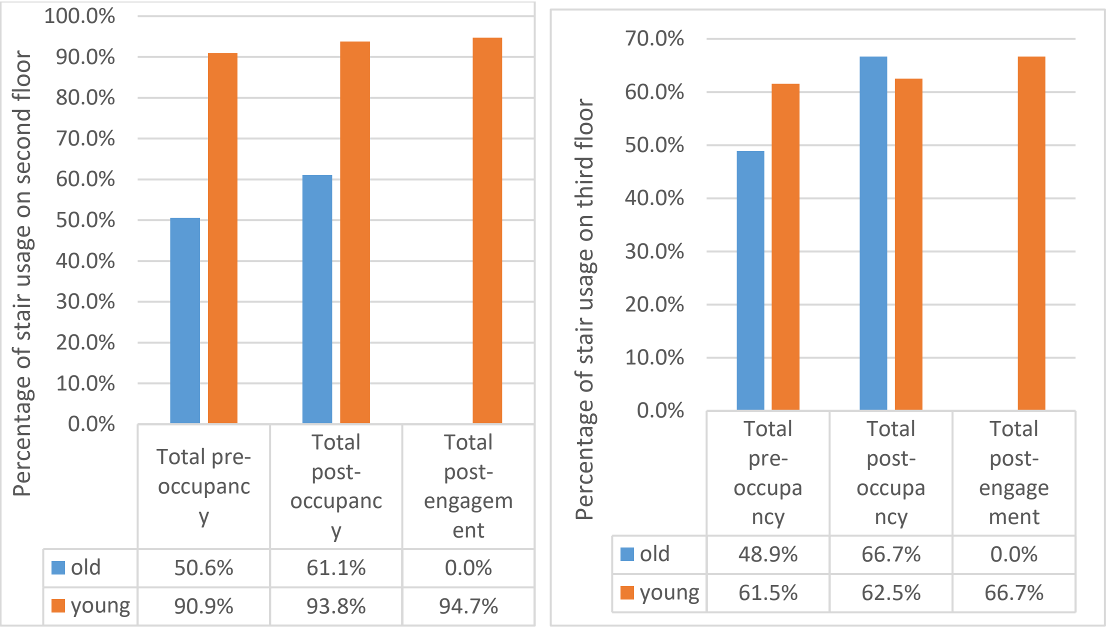


Figure 4.44 The percentage of young and older people using stairs by stage

It can be observed from the bar chart that young people have higher stair usage rates than older people in most of the stages. However, after conducting a two-way ANOVA for the data on the two floors, the significant values P1 (left) = 0.101 > 0.05, P2 (right) = 0.362 > 0.05, so the influence of age was not statistically significant. In addition, no statistics showed that the interventions had significant effect on stair usage according to the age groups of people (P3 (left) = 0.534 > 0.05, P2 (right) = 0.571>0.05).

***Sex***

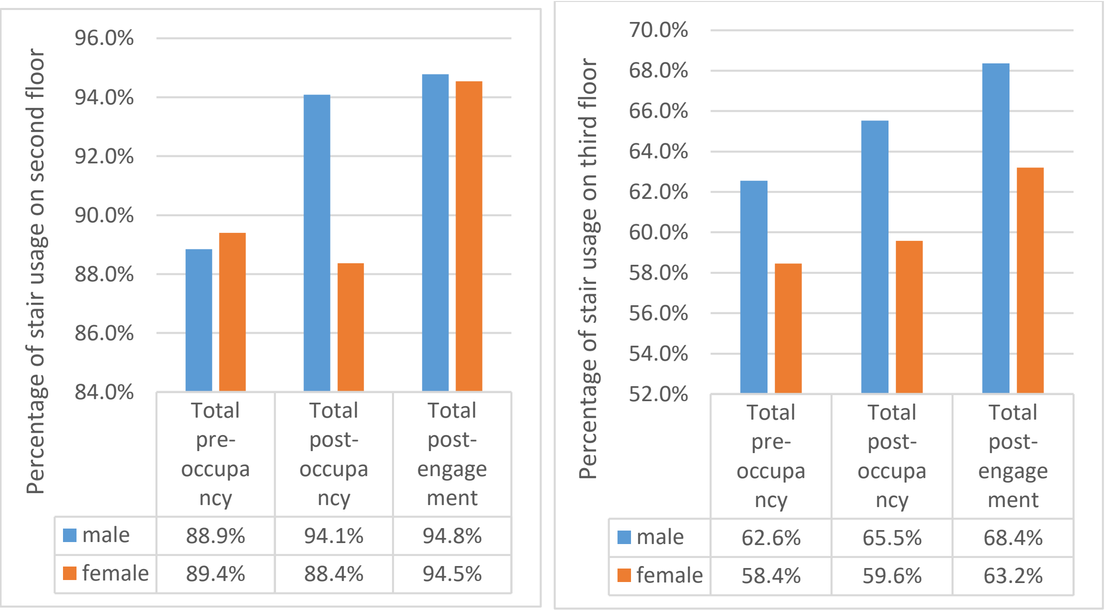


Figure 4.45 The percentage of males and females using stairs by stages.

Observing the bar chart, males seemed overall more likely to use the stairs than females during the observations. After conducting a two-way ANOVA for the data, statistically no evidence was found that males used stairs more often than females on the second floor ($P1 = 0.458 > 0.05$) and the intervention did not show any significant effect ($P3 = 0.272 > 0.05$). However, the statistics showed that males were 5% more likely to use stairs than females on the third floor ($P2 = 0.011 < 0.05$) and the interventions did indeed have significant effects on the increase of stair usage over time ($P4 = 0.029 < 0.05$).

### *Directions*

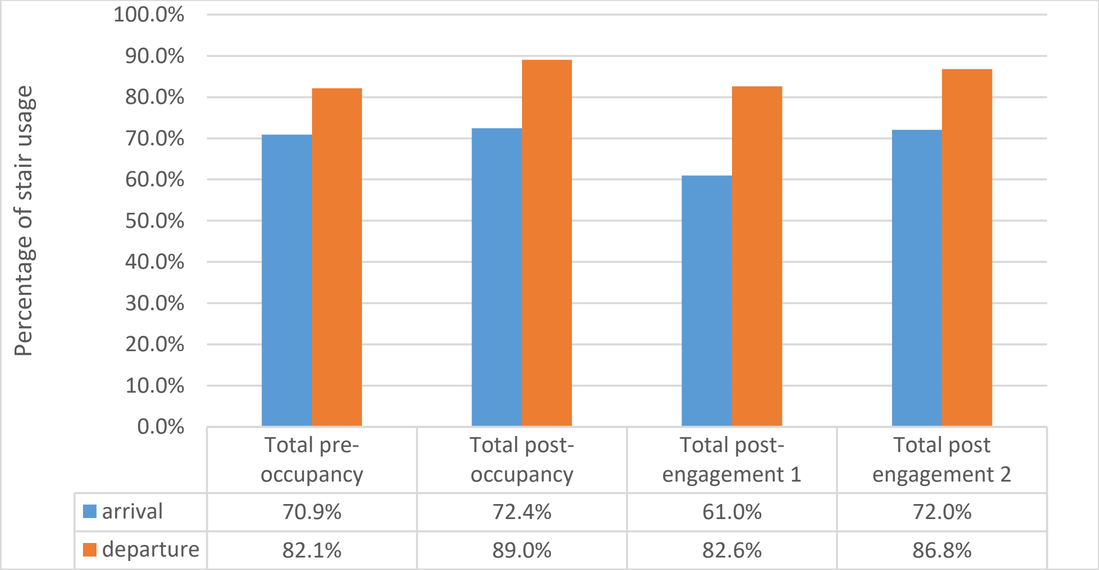


Figure 4.46 The percentage of people using stairs when travelling in different directions by stage.

Observing the bar chart, people used the stairs more often when descending. After conducting a two-way ANOVA for the data, the test found that people were indeed 16% more likely to use stairs when descending ($P= 0.005 < 0.05$). Again, the interventions are found to have no significant effects on the changes in stair usage rates ($0.174 > 0.05$).

### *Groups*

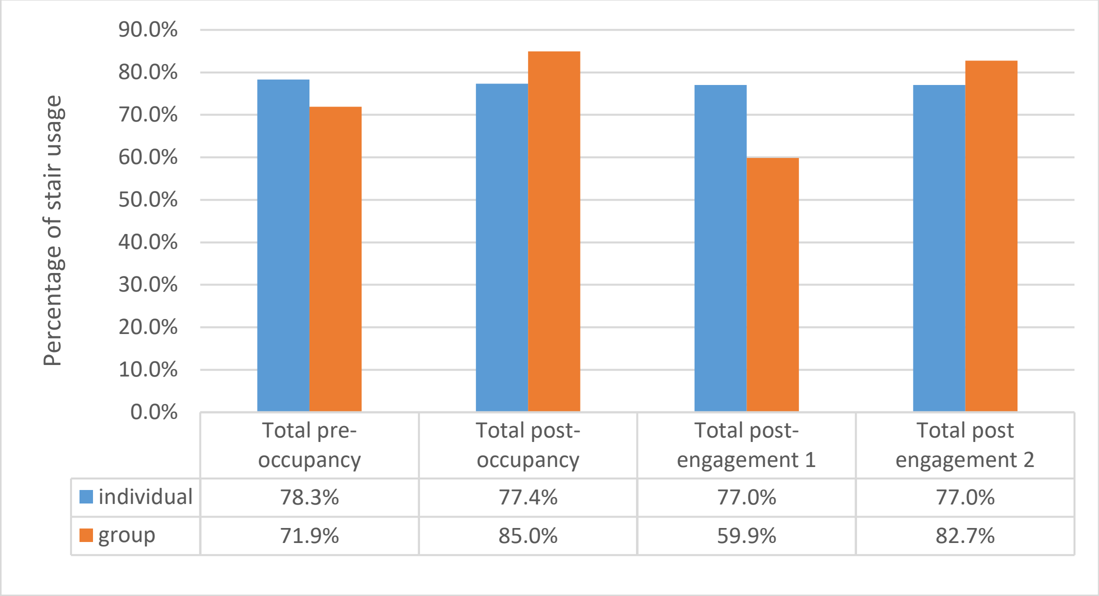


Figure 4.47 The percentage of people using stairs when travelling on their own or in groups by stage.

There was no obvious trend in this graph. After conducting a two-way ANOVA for the data, the stair usage rate was found to be unrelated to whether people were traveling in groups or not (P= 0.686 > 0.05). Furthermore, the interventions had no significant effects on the changes of stair usage rates (P= 0.501 > 0.05).

### *Floor*

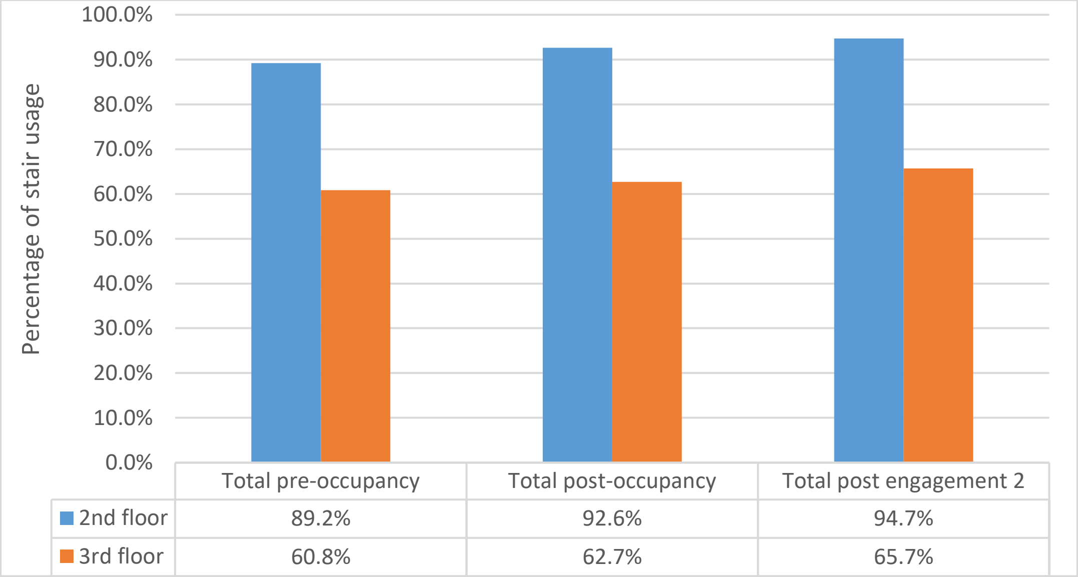
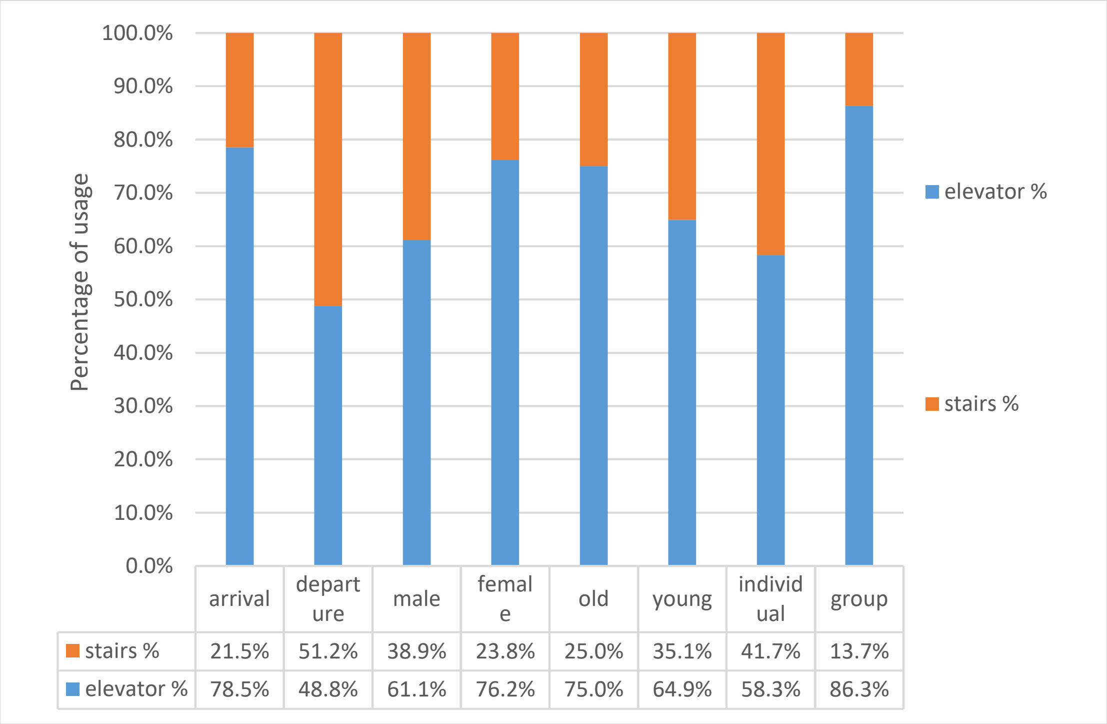


Figure 4.48 The percentage of people using stairs on different floors in the new building by stage.

Since the observer did not collect second and third floor data separately for post engagement stage 1 (only aggregated data collected from the ground floor), only post-engagement stage 2 data were included in this analysis. The main findings from the observations were that people on the second floor used the stairs more often than those on the third. After conducting a two-way ANOVA for the data, second-floor occupants were found more likely to use the stairs than third-floor subjects ($P= 0.001 < 0.05$), and this was consistent with our findings in the previous section (figure 4.35). However this time, interventions also had significant effects on stair usage rates ($P= 0.024 < 0.05$). As the interventions continued, both 2nd floor and 3rd floor stair usage increased over time. Nevertheless, since only one of the two post engagement periods was used in this analysis, the relationship differs from the previous analysis that used both post engagement counting periods.

### 4.2.8 Comparisons for One Tenant

In this section, the research was narrowed to a single tenant. The study tried to determine whether changes to the behaviors of tenants' employees were observed.



| | arrival | departure | male | female | old | young | individual | group |
|---|---|---|---|---|---|---|---|---|
| 🟧 stairs % | 21.5% | 51.2% | 38.9% | 23.8% | 25.0% | 35.1% | 41.7% | 13.7% |
| 🟦 elevator % | 78.5% | 48.8% | 61.1% | 76.2% | 75.0% | 64.9% | 58.3% | 86.3% |

Figure 4.49 Elevator and stair usage for the tenants in pre-occupancy stage.

This particular tenant was chosen since both pre-occupancy and post-occupancy data had been collected for the tenant, and it was the only tenant for whom none of the data collections stages were on the ground floor. The figure shows that the employees of this tenant used elevators more than stairs in the pre-occupancy stage.

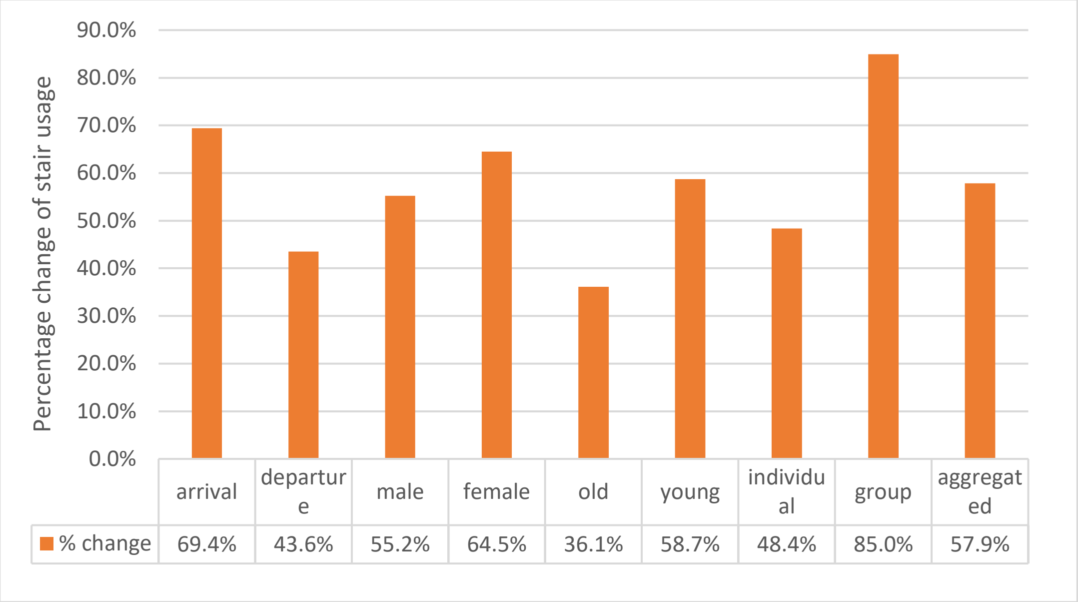


Figure 4.50 Percentage change in stair usage by the tenant from pre-occupancy stage to post-occupancy stage.

The values of the graph were calculated by subtracting the percentage of stair usage of the selected tenant in pre-occupancy stage from the percentage of stair usage in post-occupancy stage. Stair usage increased for all categories, the minimum increase being 36%. The previous section showed that floor height influenced the stair usage. This particular selected tenant was on the third floor and moved to the second floor in the new building. In addition, their previous office building had side stairs only, so that the change of building design was also expected to affect the results. In the following analysis, we want to separate the effects of floor height and building design in order to ascertain if the tenants’ stair usage indeed increased from the pre-occupancy stage to the post-occupancy stage. If that is the case, then there may be other influential building factors that can be considered in future research aside from floor height and stair design.

From the previous section (Figure 4.35), it was found that the people’s stair usage decreased with an increase in floor height. Based on the study of the EV3 building (the only previous building with data for both second and third floors), a regression test was performed in order to find the numerical relationship between stair usage and floor height.

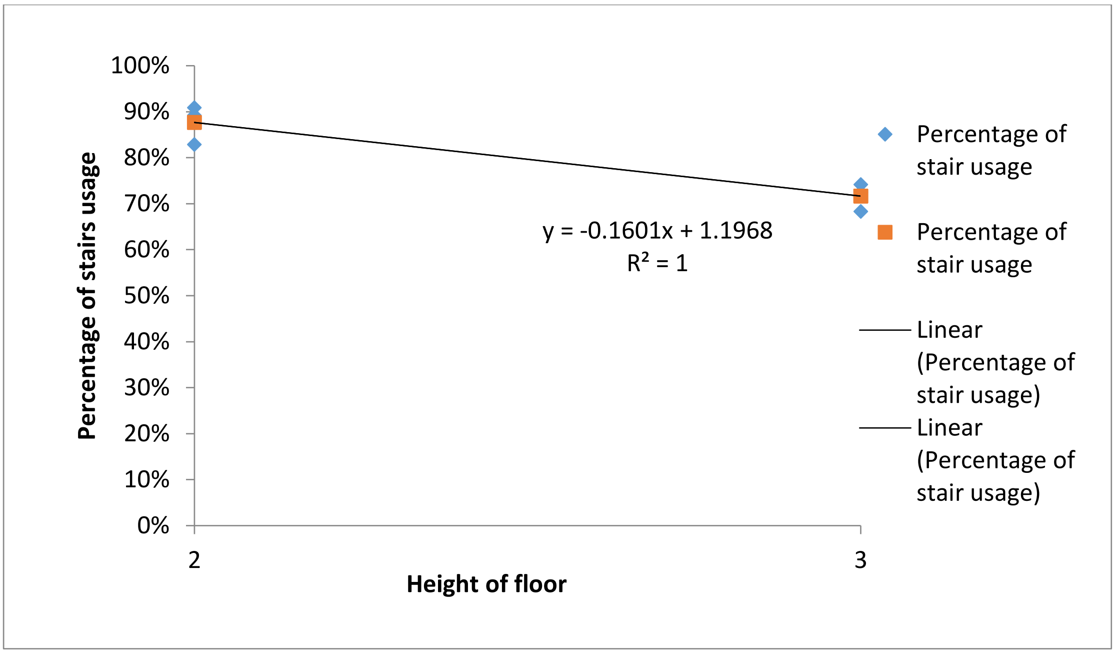


Figure 4.51 Regression of percentage of stair usage on floor height.

The regression showed a strong relationship between the two variables with $p = 0.006 < 0.05$, and the equation: percentage of stair usage = - 0.1601 x floor height (from 2 to 3) + 1.1968 can be used for the percentage of stair usage on different floors. Based on the graph, moving from the third floor to the second can increase stair usage by 16.0 %. It should be noted that this relationship is limited to only second and third floors since the relationship between stair usage and floor height was not necessarily linear (see figure 4.35, 4.36 and 4.37 in previous sections).

Then, in order to understand the change in stair usage when people moved from a building design with side stairs only to a design with a centrally prominent staircase, a regression test was done between the two previous tenants’ buildings with different building designs.

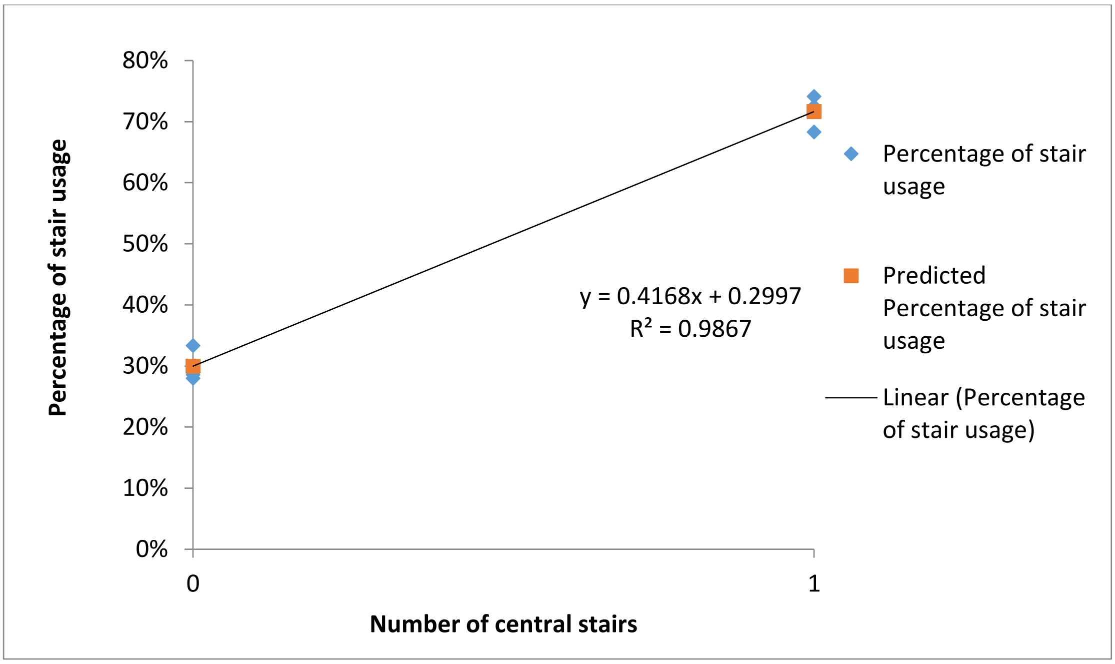
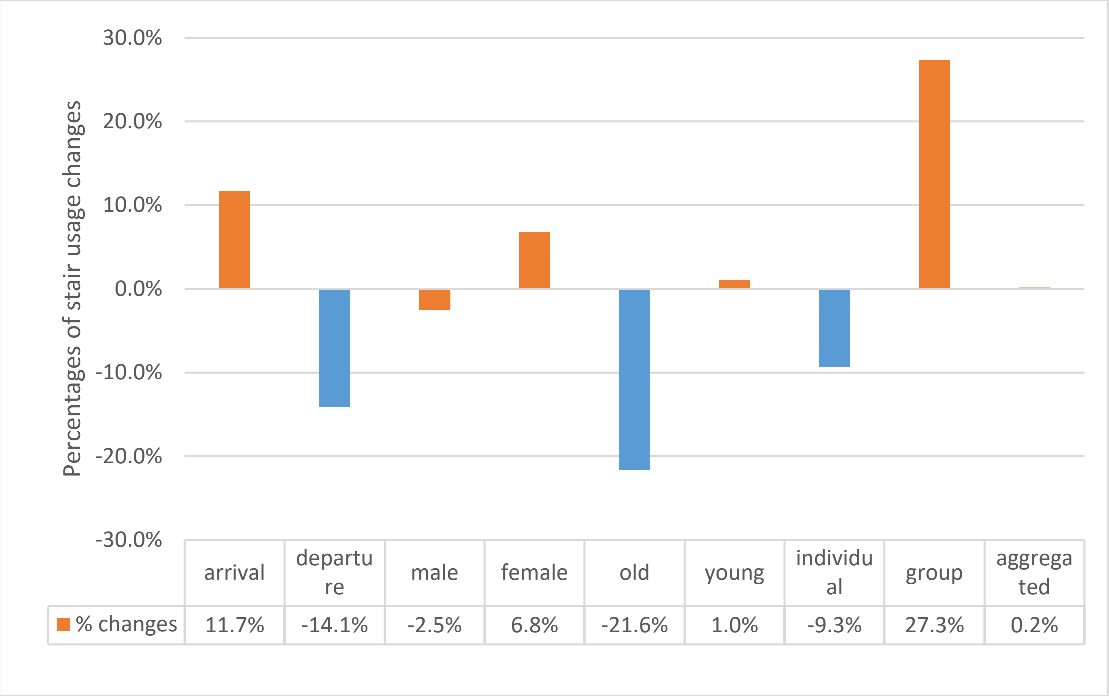


Figure 4.52 Regression of percentage of stair usage on the number of central stairs in the building design.

The regression showed a strong relationship between the two variables with p = 6.7E-05 < 0.05, and the equation: percentage of stair usage = 0.4168 x number of central stairs (from 0 to 1) + 0.2997 can be used for the percentage of stair usage in differently designed buildings. Based on the graph, moving from a building with only side stairs to a building with a prominent central staircase design can increase stair usage by 41.7 %.

Combing the two graphs, if we assume the two influential factors of floor height and stair design are independent to each other, then the stair usage of the selected tenant's employees would increase by 16.0% + 41.7% = 57.7%. If this percentage of change is subtracted from figure 4.50, then the following graph can be made:



| | arrival | departure | male | female | old | young | individual | group | aggregated |
|---|---|---|---|---|---|---|---|---|---|
| 🟧 % changes | 11.7% | -14.1% | -2.5% | 6.8% | -21.6% | 1.0% | -9.3% | 27.3% | 0.2% |

Figure 4.53 Percentage change of stair usage of the selected tenant from pre-occupancy stage to post-occupancy stage. (after removing two main influential factors)

As shown in Figure 4.53, five out of the eight categories still went to positive values after subtracting the changes brought about by the two selected factors, and the other three categories went to negative values, while the aggregated value remained almost the same. On the one hand, it showed that the floor height and stair design of a building are the two main factors that affect stair usage in a building. The negative value can indicate that there may be some correlations between these two factors which may be examined in future research. On the other hand, the negative values can also indicate that there are some other factors that may affect stair usage negatively. Lastly, some categories consistently showed positive values while other showed negative values, indicating that for different categories there may be some other influential factors which impact each of the demographic groups differently.

In conclusion, it may not be proper to use the sum of the two influential factors to present all the main effects, and the interactions between these two factors as well as all the other potential influential factors remain to be studied.

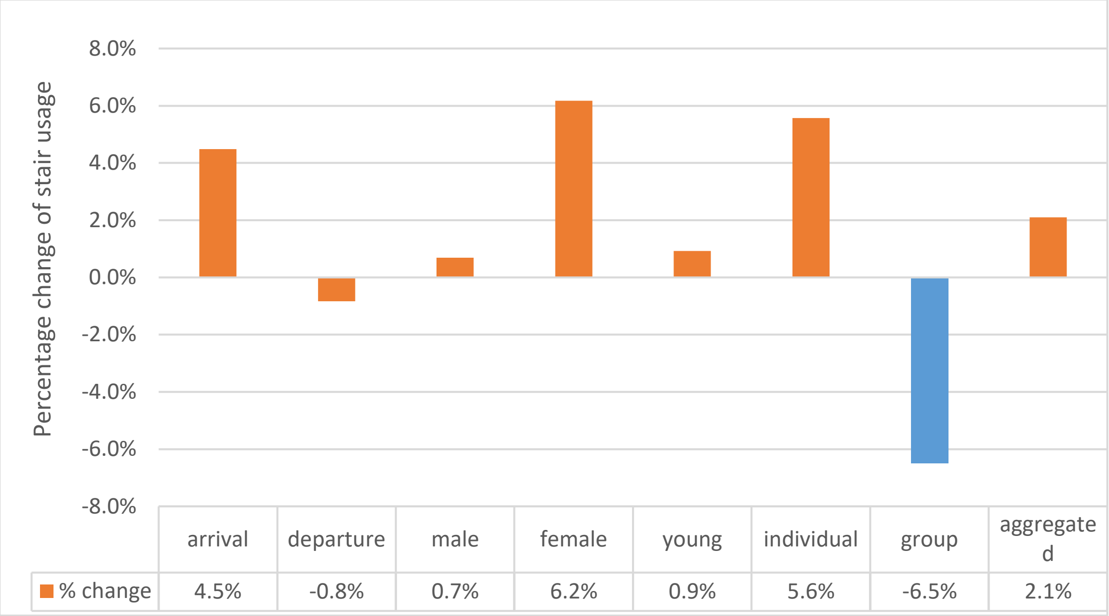


Figure 4.54 Percentage change of stair usage of the selected tenant from post-occupancy stage to post-engagement stage.

As the Figure 4.54 shows, only a slight increase was observed after four workshops/activities were conducted as interventions. Some of the categories even exhibited decreased stair usage. For the “older” people category, since no older people were observed on that particular post-engagement observation day, the percentage was 0% and therefore this category was not shown in the graph.

### 4.2.9 Sensor Consistency Analysis

In this section, we wanted to test if the sensor counts were consistent within a week and/or among weeks. A single factor one-way ANOVA was used to identify the consistency of sensors among weeks and regression tests were used to identify the consistency of sensors within a week.

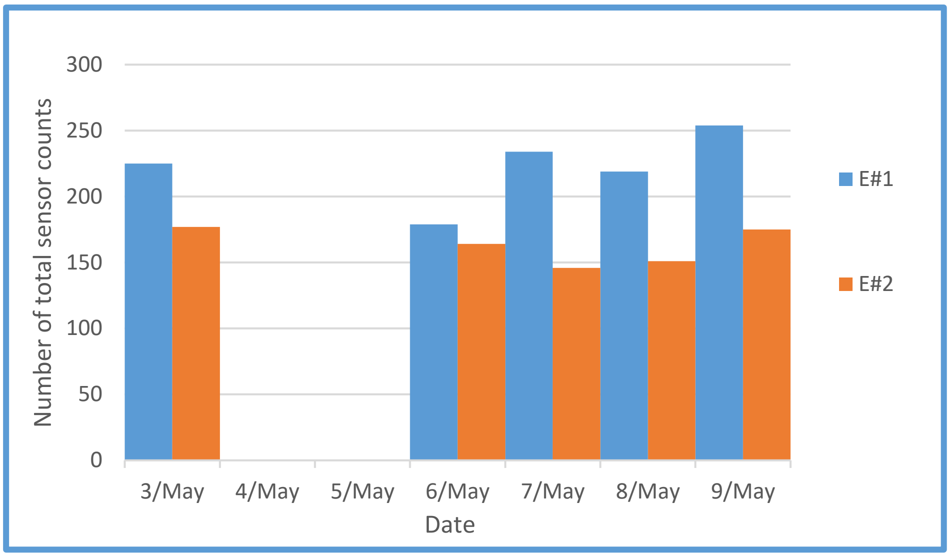


Figure 4.55 Sensor counting summary for two elevators on the ground floor.

For E#1, the average daily counts for the week = 222.2, and the range of count varied from 179 (-19.4%) to 254 (14.3%), a regression test showed P = 0.242 > 0.05. For E#2, the average daily counts for the week = 162.6 and the range of count varied from 146 (-10.2%) to 177 (8.9%), a regression test showed P = 0.259 > 0.05. For both E#1 and E#2, no significant correlation was found between the dates and the counts from the sensors.

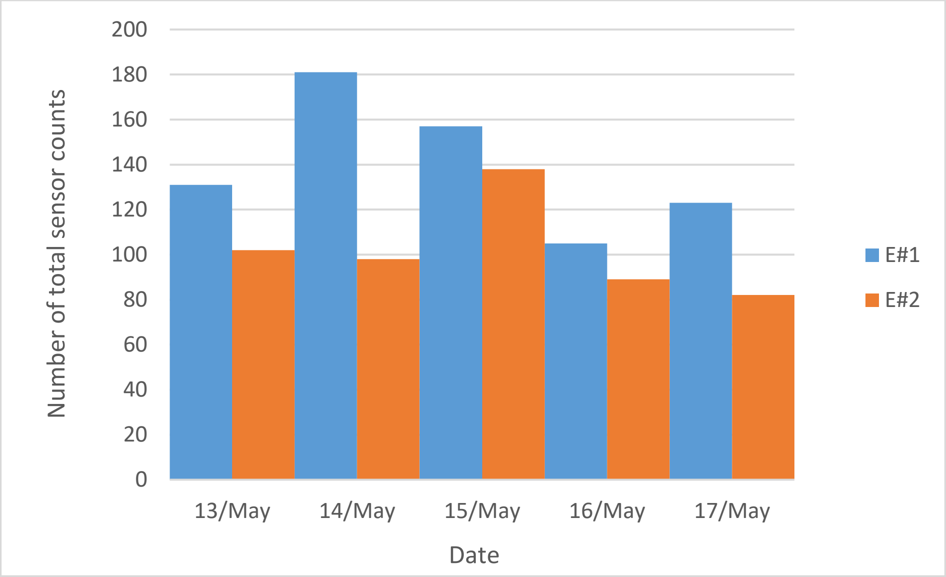


Figure 4.56 Sensor counting summary for two elevators on the second floor.

The average daily count for the week on E#1 = 139.4 and the range of count varied from 105 (-24.7%) to 181 (29.8%), a regression test showed P = 0.405 > 0.05. The average daily count for the week on E#2 = 101.8 and the range of count varied from 82 (-19.5%) to 138 (35.6%), a regression test showed P = 0.555 > 0.05. No significant correlation was found between the dates and the counts from the sensors for either E#1 or E#2.

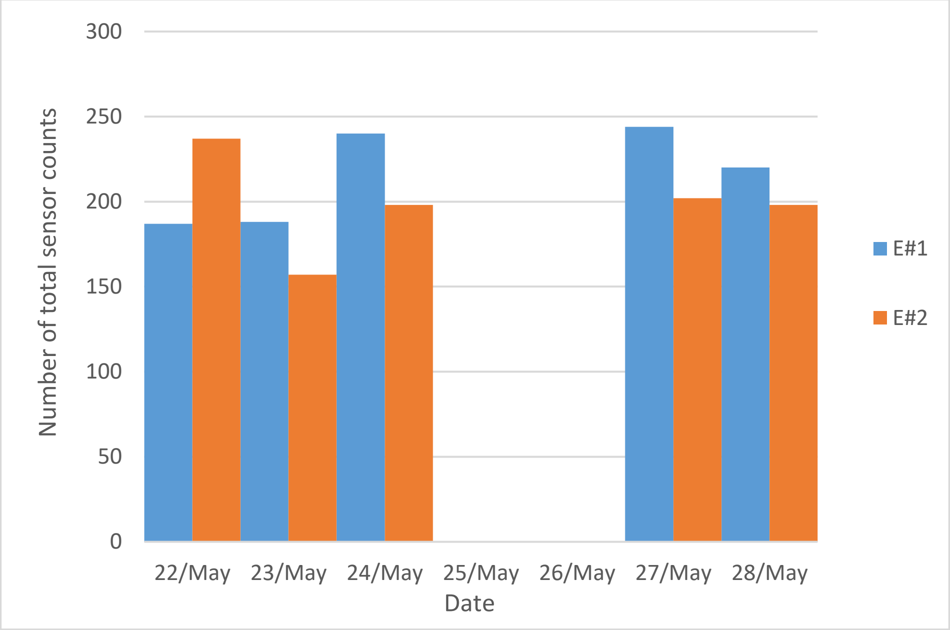


Figure 4.57 Sensor counting summary for two elevators on the third floor.

The average daily count for the week on E#1 = 215.8 and the range of count varied from 187 (-13.4%) to 244 (13.1%), a regression test showed P = 0.709 > 0.05. For E#2, an average daily count for the week = 198.4 and the range of count varied from 157 (-20.9%) to 237 (19.5%), a regression test showed P = 0.657 > 0.05. No significant correlation was found between the dates and the counts from the sensors for either E#1 or E#2.

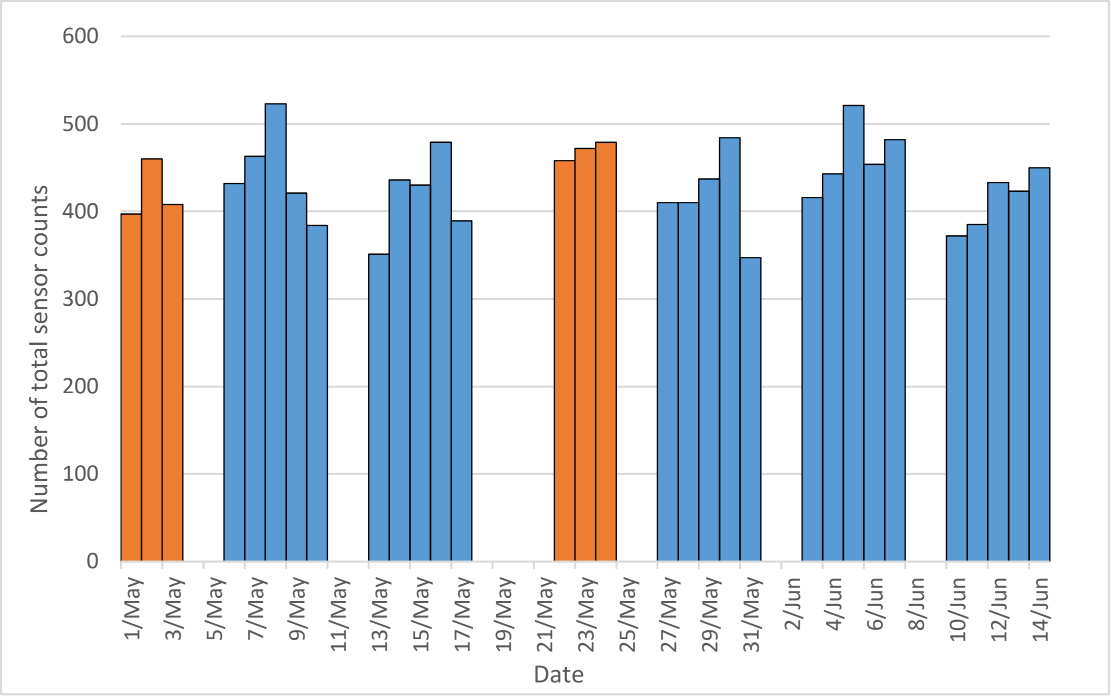


Figure 4.58 Sensor counting summary for the sensor S#1.

This figure represents the sensor consistency analysis for the central stair sensor between the ground and the second floor. Thirty-one days of sensor-counting data were available for the central stairs as shown in Figure 4.58. Both among-week and within-week consistency analyses were done, however, only 25 days of data were chosen for the statistical analysis since these days recorded entire weeks without any missing days in the weeks (marked in blue). The bars marked in orange were therefore not included in the analysis. An average daily sensor count = 433.8 and the range of count varied from 347 (-20.0%) to 523 (20.6%). Regression tests for each of the weeks (blue bars from left to right marked as week 1 to week 5) showed the significant values as follows: Week 1: P= 0.483, Week 2: P= 0.521, Week 3: P= 0.790, Week 4: P= 0.321, Week 5: P= 0.086 > 0.05. No significant correlation was found between the dates and the counts from the sensors for any week. For the among-weeks analysis, an ANOVA test showed P= 0.298 > 0.05, so again, no significant correlation was found between the weeks and the counts from the sensors.

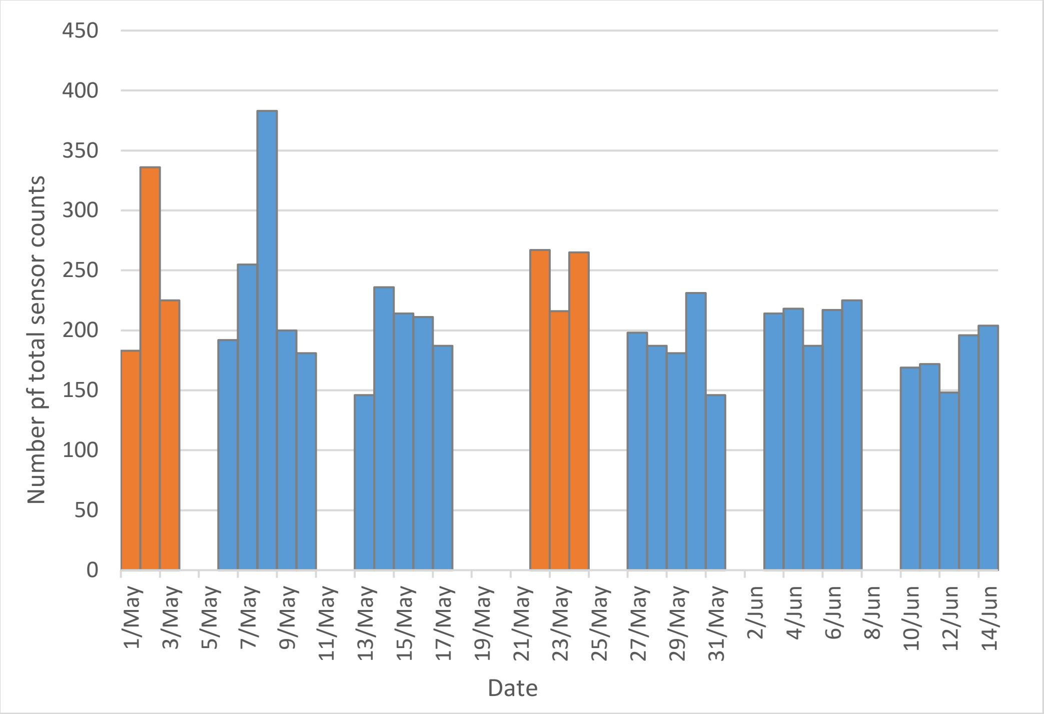


Figure 4.59 Sensor counting summary for sensor S#2

This figure details sensor consistency analysis for the central stair sensor between the second and the third floor. As with sensor#1, 31 days of sensor-counting data were collected and shown in Figure 4.59, and again only blue bars in the figure were included in the statistical analysis. On May 2nd and May 8th, the number of counts was much higher than on other days, possibly because there were many visitors in the building on those days or some activities (e.g. guided tours) were held. The average daily sensor count for the week = 212.6 and the range of count varied from 146 (-31.3%) to 383 (80.2%). Regression tests for each of the weeks showed the significant values as follows: Week 1: P= 0.815, Week 2: P= 0.669, Week 3: P= 0.612, Week 4: P= 0.714, Week 5: P= 0.224 > 0.05. No significant correlation was found between the dates and the counts from the sensors for any week. The ANOVA test on among-week analyses showed P=0.220 > 0.05. Yet again, no significant correlation was found between the weeks and the counts from the sensors

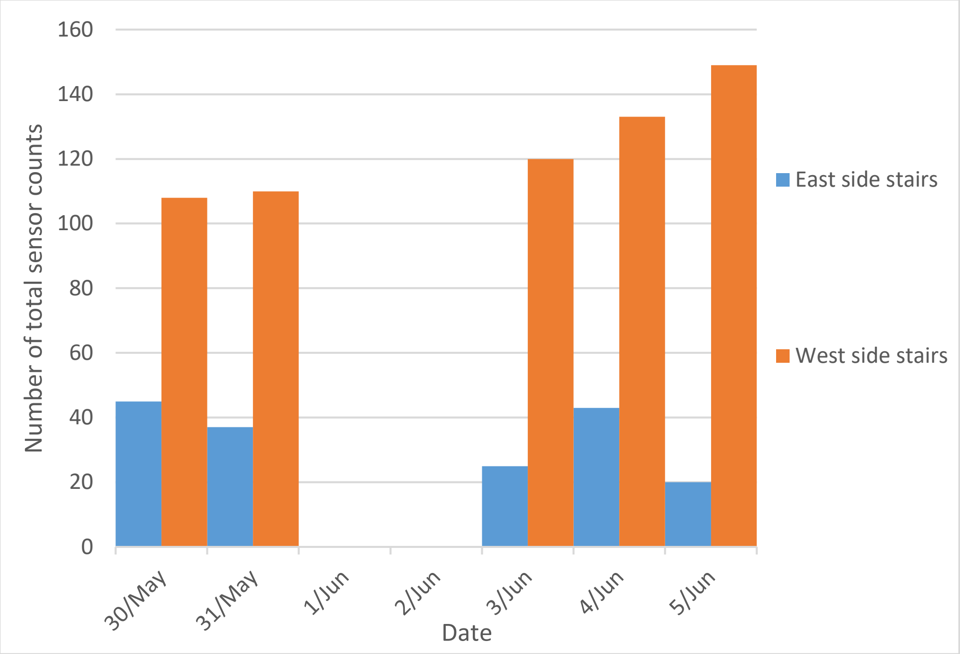


Figure 4.60 Sensor counting summary for the sensors E#1 and E#2.

Two people-counting sensors (E#1 and E#2) were moved to cover the two side stairs on the second floor (sensors located between the ground and the second floor). E#1 covered the east side stairs, and E#2 the west (consistent with labels in the previous sections). The average daily E#1 count for the week = 34 and the range of count varied from 20 (-41.2%) to 45 (32.4%), a regression test showed P = 0.537 > 0.05. The average number of E#2 counts for the week = 124 and the range of count varied from 108 (-12.9%) to 149 (20.2%), a regression test showed P= 0.487 > 0.05. No significant correlation was found between the dates and the counts from the either of the sensors.

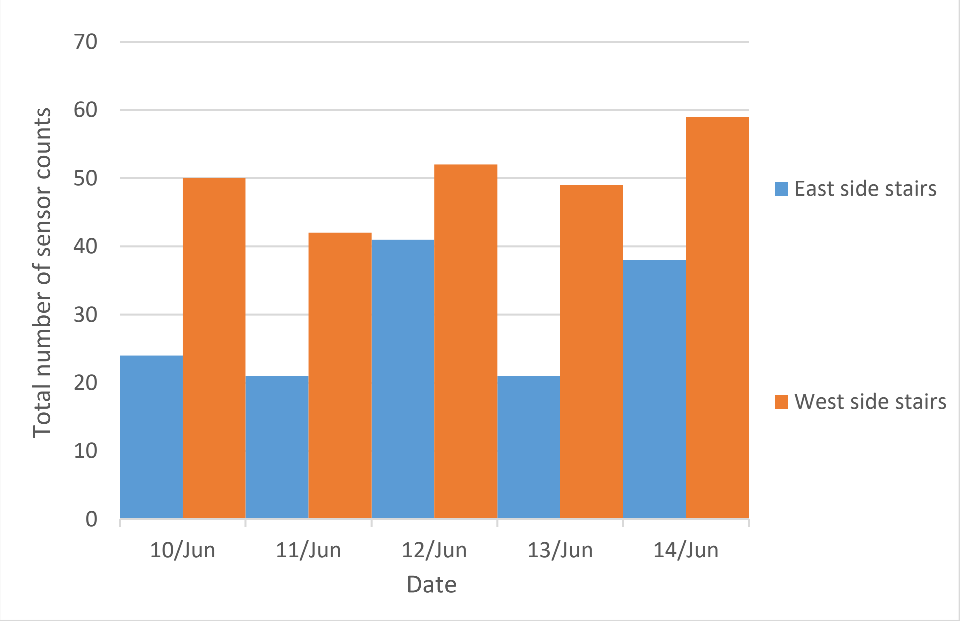


Figure 4.61 Sensor consistency analysis for the sensors E#1 and E#2.

Again, two people-counting sensors were moved to cover the two stairs on the third floor (sensors located between the second and the third floor). E#1 covered the east side stairs and E#2 the west. The average daily E#1 count for the week = 29 and the range of count varied from 21 (-27.6%) to 41 (41.4%), a regression test showed P = 0.441 > 0.05. The average number of E#2 counts for the week = 50.4 and the range of count varied from 42 (-16.7%) to 59 (17.1%), a regression test showed P =0.238 > 0.05. No significant correlation was found between the dates and the counts from either of the sensors.

### 4.2.10 Sensor Accuracy and Sensitivity Analysis

In this section, the accuracy and sensitivity of the people-counting sensors used in this research was tested. The procedures included testing sensor counting in different locations and orientations and comparing the sensor-counted data to observational data.

#### *First Test of the Sensor Accuracy*

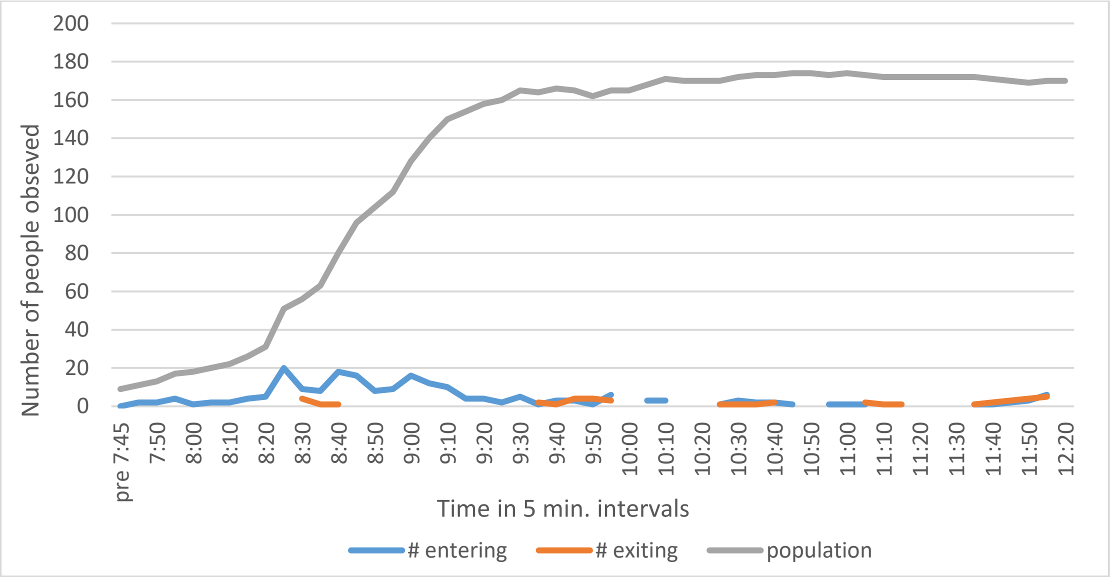


Figure 4.62 The observed count of people using the atrium door to the car park, 26th Feb 2019.

The graph above displays the raw data of arrival times for the building population without any adjustments and estimations. The total number of people observed was 170 as shown by the gray line. The population at the beginning of the data collection was 9 instead of 0, since we counted the number of vehicles in the parking lot and estimated the population by counting each car as one person’s arrival. (the initial data points in the graph were in 5-min. intervals)

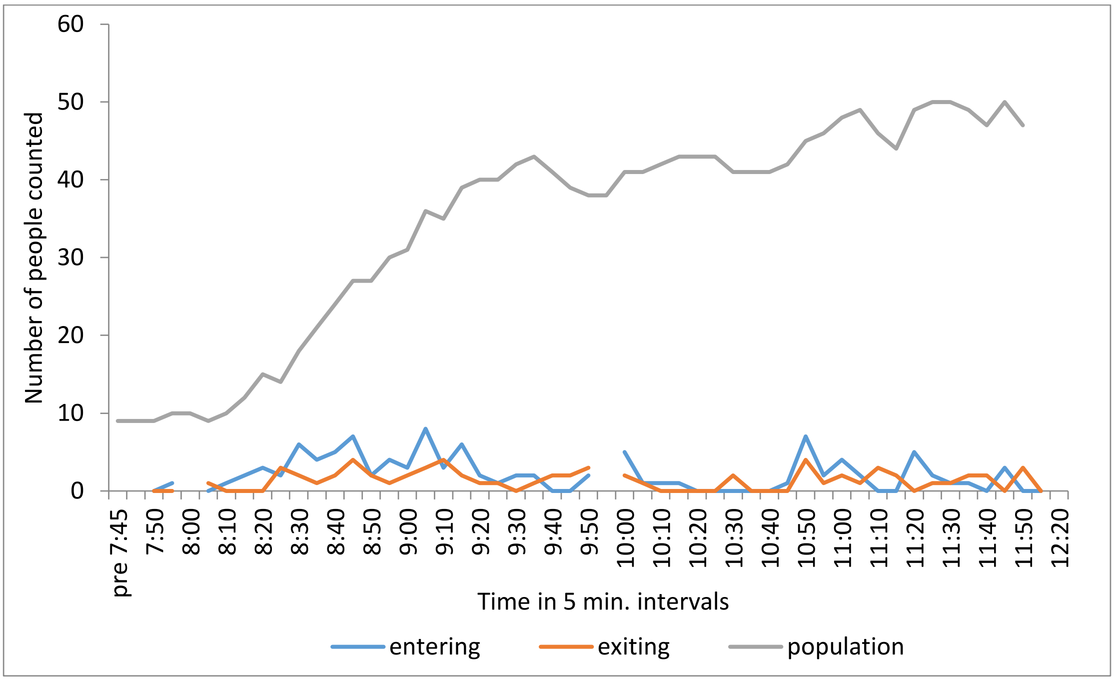


Figure 4.63 Sensor count of people using the atrium door to the car park, 26th Feb 2019.

The same population estimation was done for this graph using sensor counts. As indicated by the graph, the total number of people counted by the sensor was just 47, much smaller than the number from the observation.

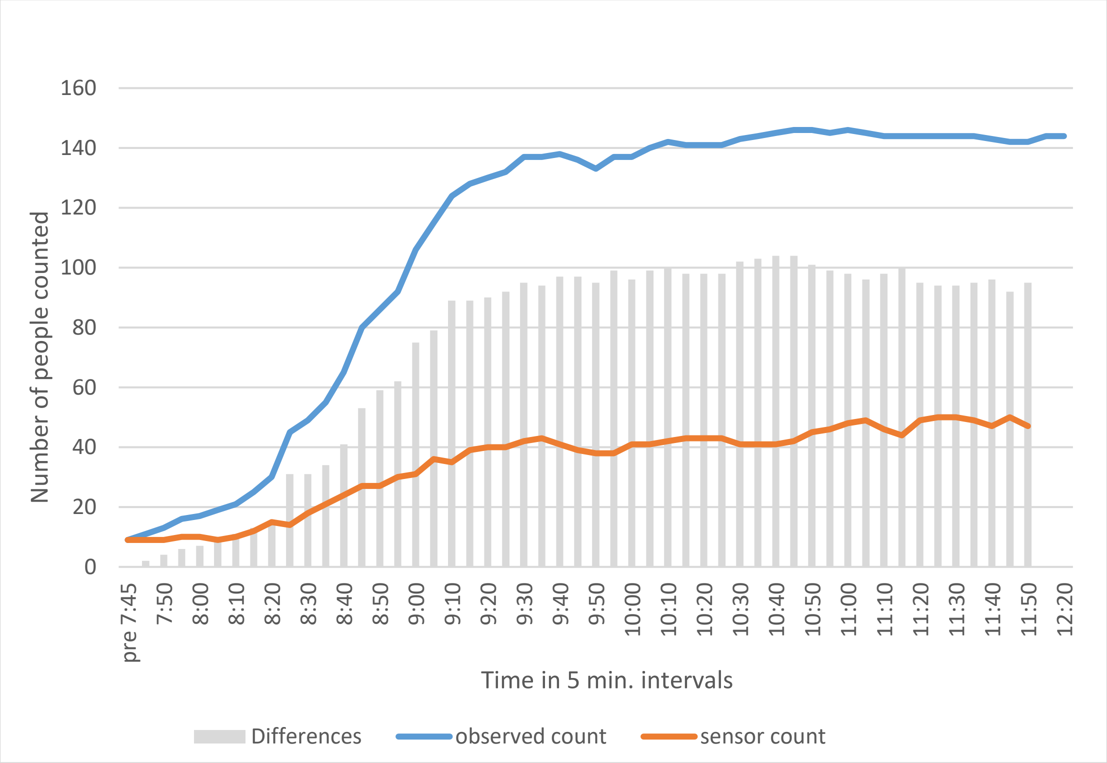


Figure 4.64 A comparison of the observed count and the sensor count population based on arrivals and exits through the atrium door to the car park, 26th Feb 2019.

The observed population in Figure 4.64 was adjusted in order to better estimate the responses of the sensor. “False entry” and “false exit” numbers were added to the calculation of the population. A “false entry” or “false exit” means that a person entered the sensor’s sensing area from a certain direction (left or right) but did not actually enter or leave the building. However, the sensor was very likely to record those people. So, false entries and exits were recorded in order to simulate the acts of the sensor and understand whether sensor data could be tweaked to match observation data. The gray bars in the graph indicate the differences between the two data sets. It was obvious that the sensor missed a lot of people.

Since the traffic flow in the morning was usually busy and most people were observed in groups, it was necessary to test whether the sensor would be more accurate if it was placed in an area with less traffic. In the next test, the sensor was moved to the side entrance and similar observations and sensor comparisons were made.

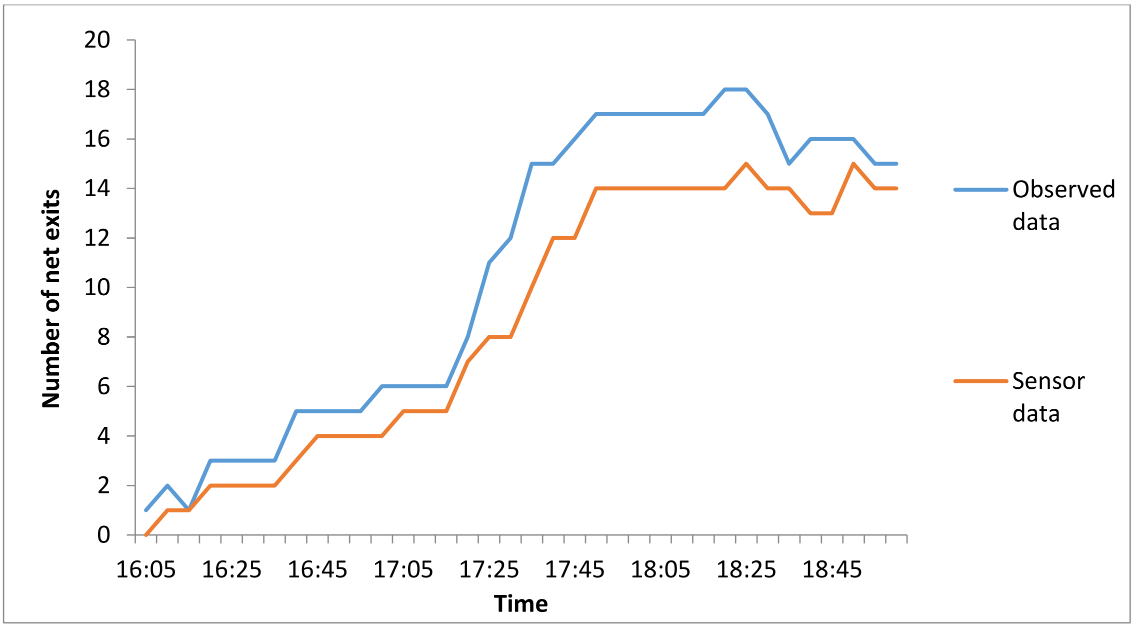


Figure 4.65 A comparison of the observed count and the sensor count of net exits through the western side door, 4 pm -7 pm, 28th Feb 2019.

The number of net exits for the y-axis of the graph was calculated by using the number of people leaving the building minus the number of people entering the building during each 5-minute time interval. Since the observation data were collected from 4 - 7 pm while most people were leaving the building, the “net exit” values were positive.

Comparing figure 4.65 to figure 4.64, it is clear that locating the sensor in a less busy area with less traffic increased the accuracy of the sensor. At the side entrance, the observed number of people leaving the building was 25 and the number entering was 10, while the sensor recorded 24 exiting and 10 entering. The overall numbers matched well, but a more detailed comparison shows larger differences for some of the 5-minute time intervals. One possible reason for the differences was that the 5-min. time intervals for the observers and sensors were not the same. For example, the observer collected data from 4 pm and noted 5-min. intervals as 4.05 pm, 4.10 pm, etc., while the sensor's 5-min. intervals started at 3.57 pm, followed by 4.02 pm, 4.07 pm, etc.

***Test of the Stair Sensor Accuracy***

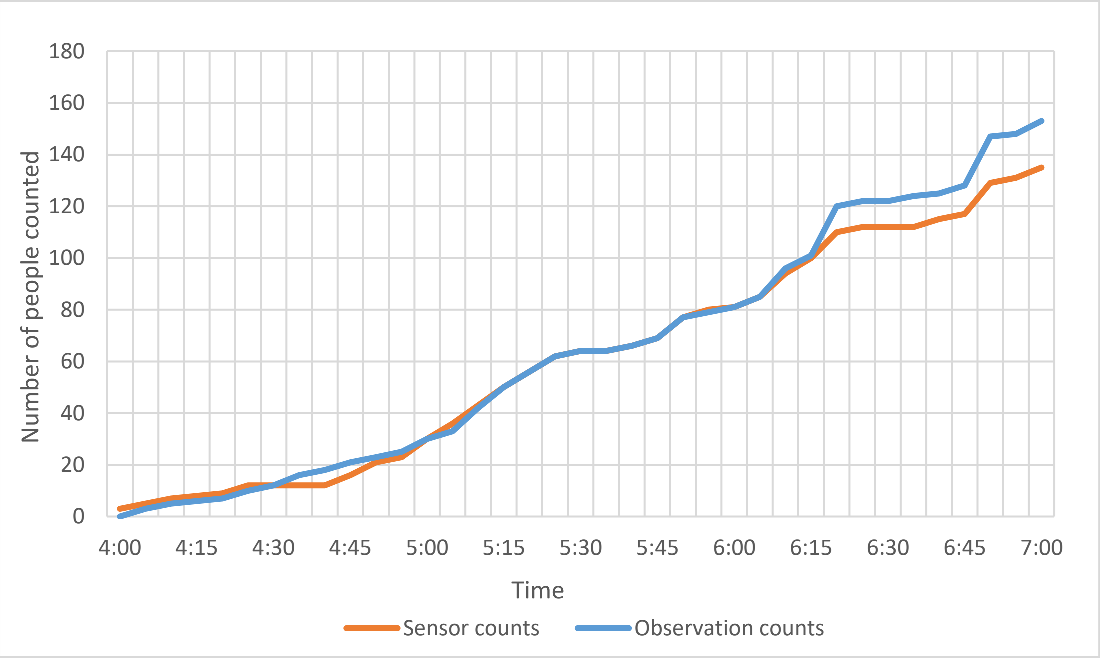


Figure 4.66 A comparison of the observed count and the sensor count of people using the central stairs (both second and third floors), 4 pm - 7 pm, 5th March 2019.

The total number was calculated by adding all of the upstairs and downstairs movements from the sensor and from the observers, respectively. The sensor recorded a total number of 135 movements while the total number recorded by the observers was 153. The sensor missed 12 % of the movements.

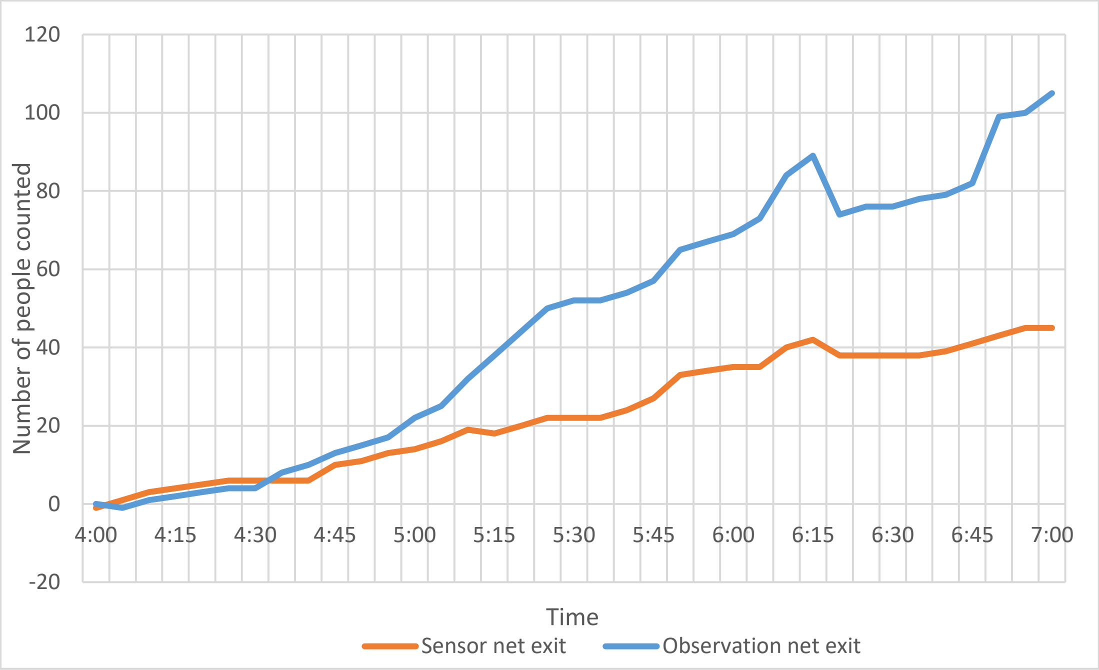


Figure 4.67 A comparison of the net exit observed count and the net exit sensor count of people using the central stairs (both second and third floors), 4 pm - 7 pm, 5th March 2019.

The net exit numbers were calculated by subtracting the number of people climbing the stairs from the number of people descending the stairs. Although 4 - 7 pm was a time when most people were leaving the building, some people went upstairs as well, so some net exit values at various time intervals were indeed negative. The ascending and descending numbers from the observers were 24 and 129 for a net exit of 105, while the sensor reported 44 people ascending and 90 people descending. The relatively large difference between the counts made the two curves trend away from each other.

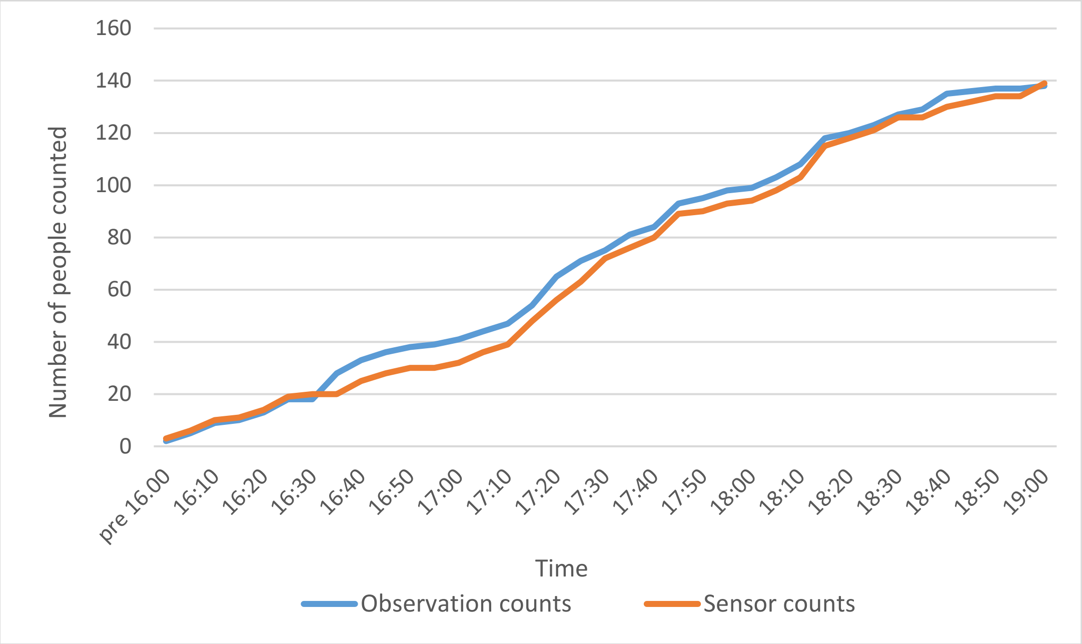


Figure 4.68 A comparison of the observed count and the sensor count of people using the central stairs (both second and third floors), 4 pm - 7 pm, 6th March 2019

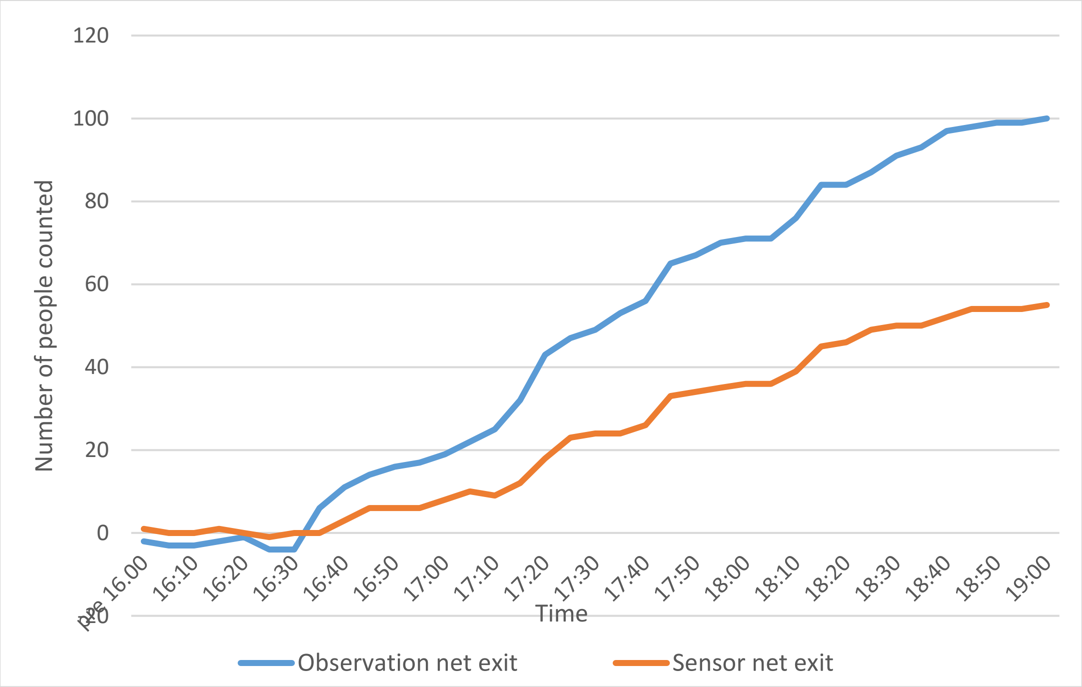


Figure 4.69 A comparison of the net exit observed count and the net exit sensor count of people using the central stairs (both second and third floors), 4 pm - 7 pm, 6th March 2019

Figure 4.68 and 4.89 showed results similar to the previous graphs: the total counts were similar, but the net exit numbers were not. The facts concerning sensor accuracy are as follows:

1. The sensor recorded smaller descending numbers and larger ascending numbers than the observer.
2. Sometimes people stood by the sensor (e.g. talking or greeting each other).
3. Sometimes people took the stairs in groups.
4. There were people ascending and descending and at the same time passing by the sensor.

Some potential errors of the sensor were found and some activities that may confuse the sensor and cause those errors were observed. It was necessary to understand the level of sensor sensitivity and the kind of mistakes it can make by conducting some sensitivity tests.

### *Test of the Sensor Sensitivity*

In the following Table 4.2, each of the tests and the corresponding sensor results for the stair sensor were recorded.

| | |
|---|---|
| Test 1 | One person walked from the left side of the sensor to the right side, three times with normal speed. |
| Results | The sensor recorded 2 left and *1 right.* |
| Test 2 | One person walked from the left side of the sensor to the right side, one time with fast (running) speed. |
| Results | Sensor recorded 1 left, (i.e. did not miss it). |
| Test 3 | One person walked from the left side of the sensor to the center, stopped there for a couple seconds and then departed to the right. |
| Results | The sensor counted *2 left* within the time interval. |
| Test 4 | Two people walked from the left side of the sensor to the right side, with a distance gap of about 10 cm away from each other (very close). |
| Results | The sensor recorded 2 left. |
| Test 5 | Two people walked from the left side of the sensor to the right side, one person totally blocked by the other (overlapped). |
| Results | The sensor recorded *1 left.* |
| Test 6 | One person walked from the left side of the sensor to the right side while the other person walked from the right side of the sensor to the left side. The two people overlapped at the center of the sensing area. |

| | |
|---|---|
| Results | The sensor recorded *1 left* |
| Test 7 | One person walked from the left side of the sensor to the right side while the other person walked from the right side of the sensor to the left side. The two people overlapped **outside of** the center of the sensing area. |
| Results | The sensor recorded 1 left and 1 right. |

Table 4.2 Stairs sensor sensitivity tests results.

The stair sensor clearly did make mistakes when counting. Sometimes the sensor was found to record movement in the wrong direction, (test 1: people going left to right, recorded as right to left). This could be an error in the sensor algorithm, or perhaps it recorded a swinging arm going in the opposite direction. This type of error seemed to happen randomly, and a frequency or pattern was not identified. The sensor showed high sensitivity in catching fast movements as can be seen from test 2. Test 3 showed that the sensor may count people multiple times if they are close to the sensor and remain immobile there for a while. Consequently, when locating the stair sensors, the researcher considered this and placed sensors where people were less likely to stop. Tests 4 to 7 showed that the sensor did well in identifying multiple moving objects directly in front of it. If people were moving in groups or moving in different directions during busy hours, the sensor would be able to make correct measurements if those people were not overlapping in the sensor's view.

Then, since it was identified that the errors generated by the sensor were mainly affected by the amount of traffic, a regression between the total percentage of errors from the sensor and the total number of people observed was done for the sensor on the stairs.

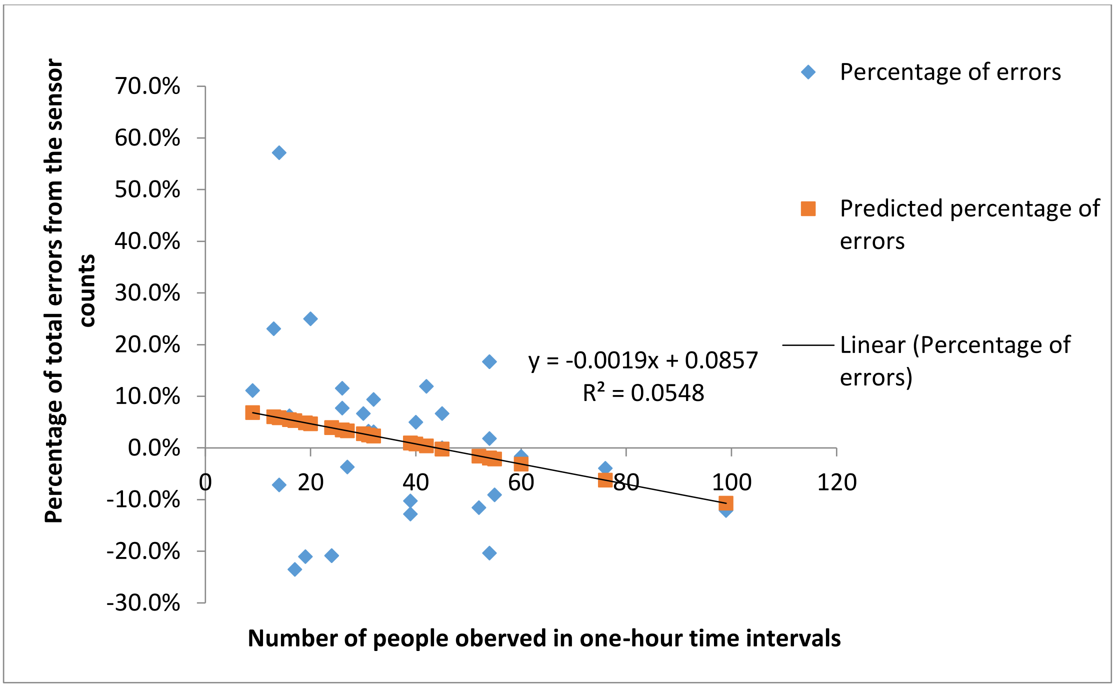


Figure 4.70 Regression plot between the percentage of errors from sensors and the number of people observed (in one-hour time intervals).

It should be noted that the entire four days' data period with 8-hours of observation were used in this plot, explaining the 32 dots included in the graph. A one-hour time interval was selected since the building has quiet and busy hours. During the quite hours, there may not be many counts in the observation so using shorter time intervals can result in many empty values. In addition, the observational and sensor-counting time intervals may not completely overlap. In that case, using shorter time intervals may bring additional errors.

As shown in Figure 4.70, sensor error is higher when the traffic is either very low or very high (only one data point). One possible reason can be that when the total number of people passing by the sensor is small, a single error accounts for a relatively large *percentage* of error. When the total number of people passing by the sensor was large, then the sensor had more opportunities to make mistakes since it was counting more frequently. As a result, the sensor worked best in a medium traffic flow (around 40 counts of people) based on the information from the graph above. However, the p value = 0.197 > 0.05 for the regression, so the relationship was not statistically significant. More data will be needed in order to test the significance of this relationship in future research.

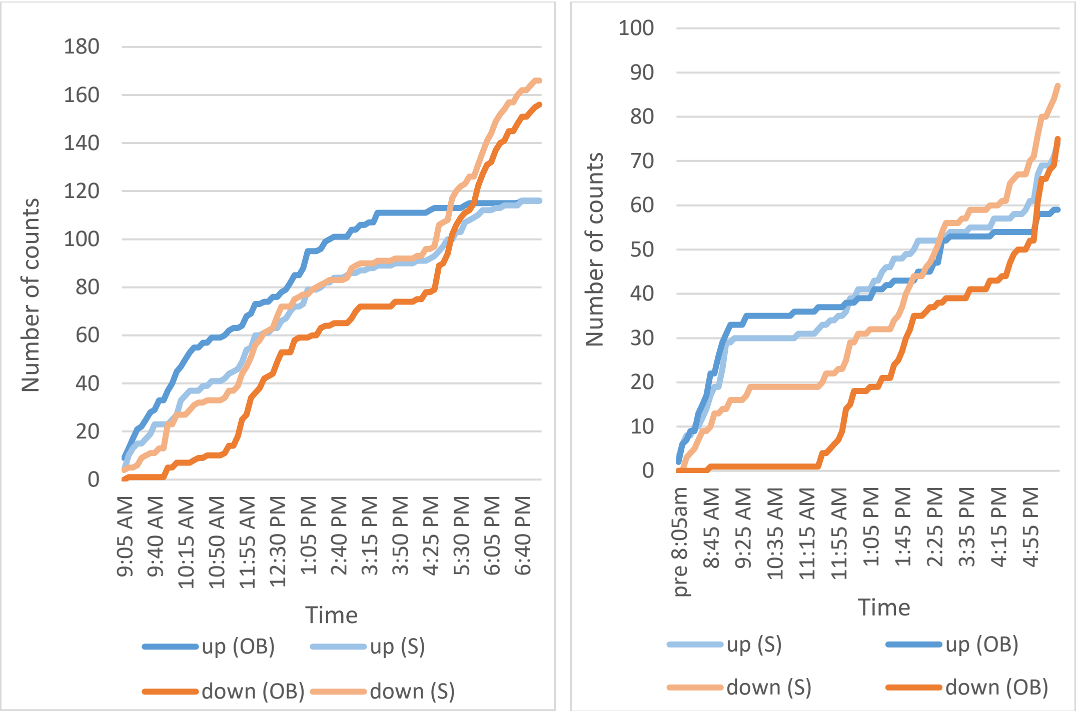


Figure 4.71 A Comparison of stair sensor observation and sensor-reporting data in both directions on second and third floors.

The numbers from the two databases for the stairs matched well. On the second floor, the observed numbers for ascending and descending were 116 and 156 respectively for the day, and the sensor reported 116 for climbing upstairs and 166 for descending. The aggregated errors by percentage are 0% for ascending and 6% more counts for descending, making a 4% error for the aggregated total. The sensitivity test above showed that the sensor may record the opposite direction of movement. Figure 4.71 shows that the sensor recorded ascending values were generally lower than the observed values while the descending values were consistently higher than the observed values. This provides another indication that the sensor sometimes records the opposite direction. On the third floor, the observed numbers for ascending and descending were 59 and 75, and the sensor reported 74 for climbing and 87 for descending. The aggregated errors by percentage are 25% for ascending and 16% more counts for descending, making the aggregated total errors 20%. The traffic on the third floor was lighter than that on the second floor but the sensor was less accurate. Possible explanations are the difference in the sensor positions and more frequent disturbances of the sensor on the third floor.

To conclude, the accuracy of the stair sensors was quite high (0-6%), such that these sensors can be used for future data collection of the total stair usage after applying the corrections for the errors. However, the sensor can be confused by movement directions so it may not be proper to use this sensor data for stair usage when people going in different directions.

The following errors can be applied to the sensor collected counts for future research as calculated from all the observational and sensor-recorded data collected: total error: -1.3%, ascending error: + 12.1%, and descending error: - 10.2%

The following table presents the sensitivity tests and results for the elevator sensors.

| | |
|---|---|
| Test 1 | Walking from left to right with the walking route parallel to the elevator doors. (Simulating people walking by the elevators from left to right) three times. |
| Results | Sensor counted *2 in and 1 out.* |
| Test 2 | Walking from right to left with the walking route parallel to the elevator doors. (Simulating people walking by the elevators from right to left) three times. |
| Results | Sensor counted *2 in and 1 out.* |
| Test 3 | Walking towards the elevator door but not entering the elevator, and then leaving very quickly. (Simulating people arriving and pressing the button but then deciding not to take the elevators). |
| Results | The sensor counted *1 in and 1 out.* |
| Test 4 | Walking towards the elevator door but not entering the elevator, and then remaining for 10 seconds. (Simulating people coming and waiting for the elevators to arrive). |
| Results | The sensor counted *1 in and 1 out*. |

Table 4.3 Elevators sensors sensitivity test results

From the results above, the elevator sensors were much less accurate than the stair sensors. Ideally, all four tests should not result in counts if no one entered the elevator. However, walking by and waiting was counted by the sensor. With all the potential errors above, two days of observations were performed for the elevator and stair sensors to examine how different the sensor data were from observed data.

***Test of the Elevator Sensor Accuracy***

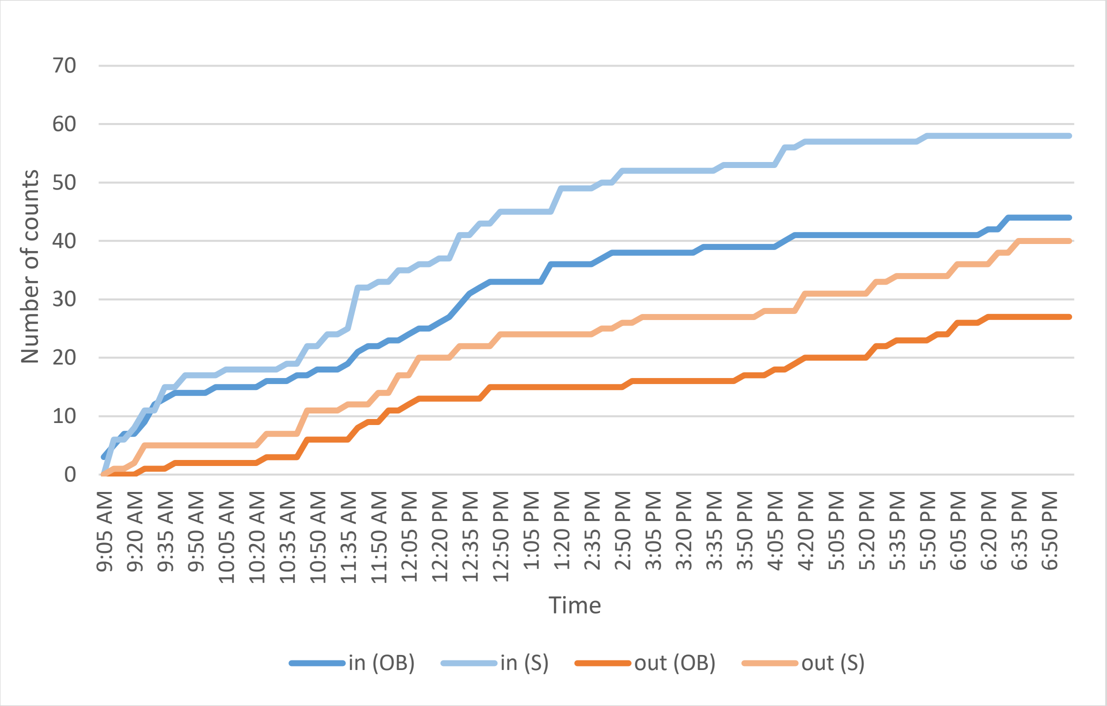


Figure 4.72 A comparison of elevator observations and sensor #1 reporting data.

The sensors recorded larger numbers than the observations for both entering and exiting the elevators. The observed numbers for entering and exiting the elevator were 44 and 27 respectively, however, the sensor reported 58 for entering and 40 for exiting. The aggregated errors by percentage were 32% more for entering the elevator and 48% more counts for exiting the elevator. However, the net movements were similar, with 17 more people observed going in and 18 more counted by the sensor as going into the elevator.

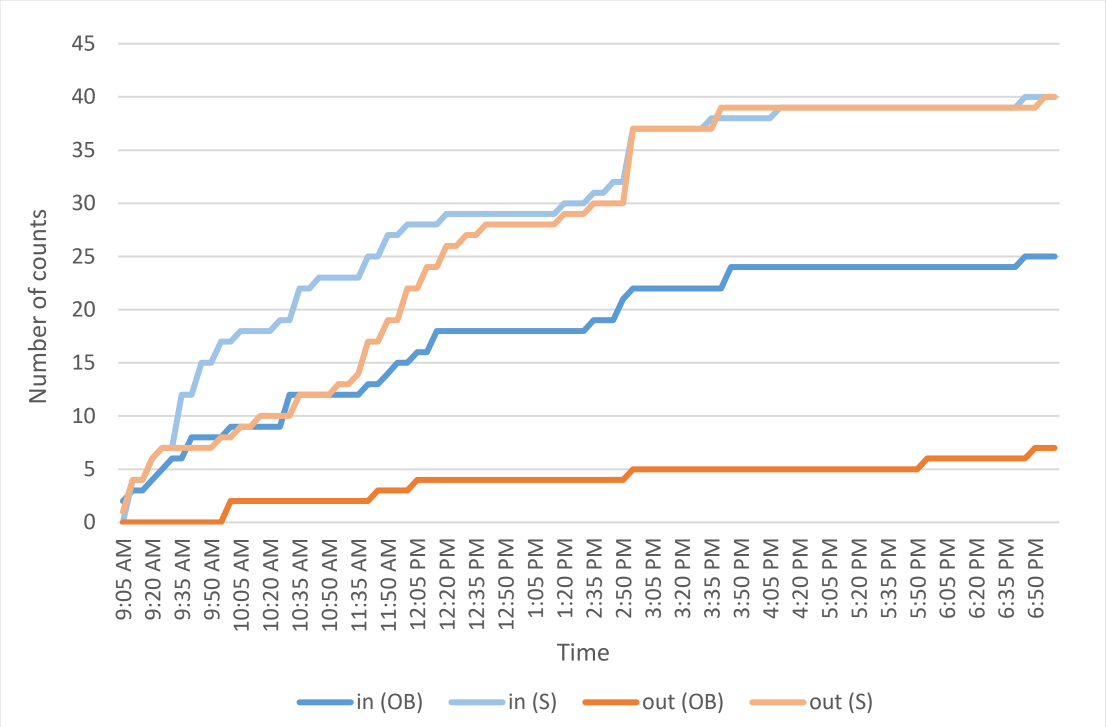


Figure 4.73 A comparison of elevator observations and sensor #2 reporting data.

The observed numbers for going in and out of elevator 2 were 25 and 7 respectively. However, the sensor reported 40 for both entering and exiting. The aggregated errors by percentage were 60% more for going into the elevator and 471% more counts for going out of the elevator. From the observation, possible reasons for the accuracy difference between the two elevators were as follows: 1. Elevator #1 was the main elevator because each time an elevator button was pressed, elevator #1 would come first. Elevator # 2 only came into play either when elevator #1 was in operation or elevator #1 was on a higher floor while elevator #2 was on the ground floor. Consequently, elevator #1 was used much more often than elevator # 2 was. 2. The main entrance of the new building (closer to the main parking lot) is the south entrance near elevator #2. Considering the different usage frequencies of the two elevators, people would in fact walk by elevator #2 more often, but take elevator #1 in the end because it came first. As a result, elevator #2 got more disturbances from the traffic using the adjacent elevator.

### *Further Elevator Sensor Accuracy Tests*

Since both elevator sensors were not very accurate, the researcher decided to change their orientations and positions in order to lower the errors produced by people walking past. First, the sensors were moved closer to the central wall where the elevator buttons are placed. It was aimed in a manner that the wall blocked part of the sensing area outside of the elevator so that fewer people walking by would be recorded. Then, a 30-degree-angle wooden wedge was added to each of the elevator sensors at the top in order to rotate the sensor inwards toward the elevators by 30 degrees, making their outside angles 10 degrees instead of 40 degrees. A smaller covering area outside of the elevator may reduce the counts from walking-by traffic.

In addition, the study wanted to test whether the traffic flow was another effective factor. The ground floor has the largest traffic flow and most movement of people, so after testing the effects from the orientation and position of the sensors, they would be moved to the second floor and then the third floor to ascertain whether their accuracy can be further improved in a less populated area.

All the tests followed a schedule of 8 hours per day: 8 am - 10 am, 10:30 am - 12:30 pm, 1 pm - 3 pm, 3:30 pm - 5:30 pm. This schedule included both busy and quiet hours in the building and the 8 hour span would also be long enough for a representative comparison of the two data sets. The results after both changes above were as follows:

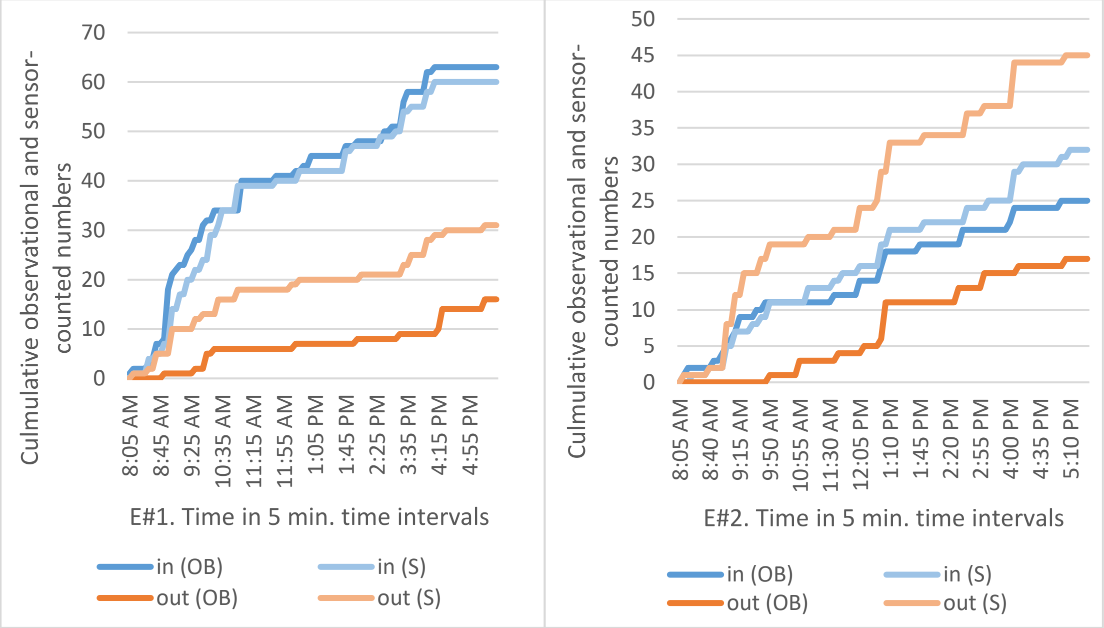


Figure 4.74 Comparisons of elevator sensor data and observational data in both directions after changing their positions.

These cumulative curves were made by adding values of a certain time interval on the net values of the previous time intervals so the differences were accumulated. Ideally, if the data from elevator sensors and observations matched well, the curves would overlap by 100%. Here the sensor for the elevator #1 (E#1 sensor) counted a total of 3 (5%) fewer people going in and 15 (94%) more people going out than the observer, while the E#2 sensor counted 7 (28%) more people going in and 28 (165%) more people going out than the observer. Comparing the two sensors, E#1 sensor was more accurate than E#2 sensor. Furthermore, the count of people entering the elevator was much more accurate those exiting elevator. The reason for this is not clear at this stage.

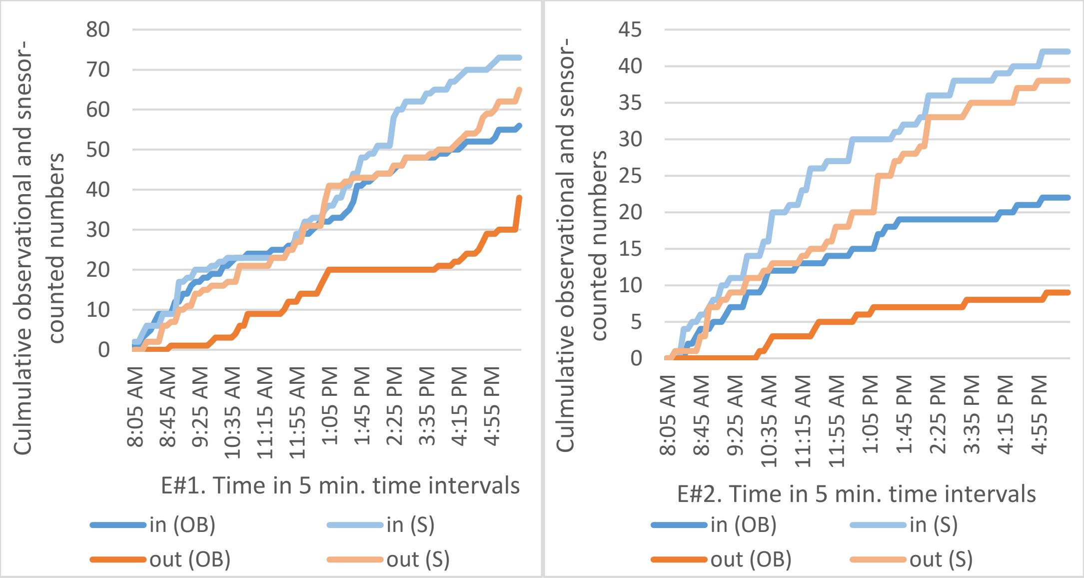


Figure 4.75 Comparisons of elevator sensor data and observational data in both directions after changing their orientations.

E#1 sensor counted a total of 17 (30%) fewer people going in and 27 (71%) more people going out than the observer, while the E#2 sensor counted a total of 20 (91%) more people entering and 29 (322%) more people going out than the observer. Sensor accuracy therefore did not improve much and the E#2 sensor actually had a decreased performance. Theoretically, changing the position and orientation should improve sensor accuracy, however, the improvements were not apparent in the results. Further tests were done in order to see if improvements could be achieved.

Using the same orientation and position, the sensors were moved to the second and the third floors to examine whether the accuracy changed due to different traffic flows.

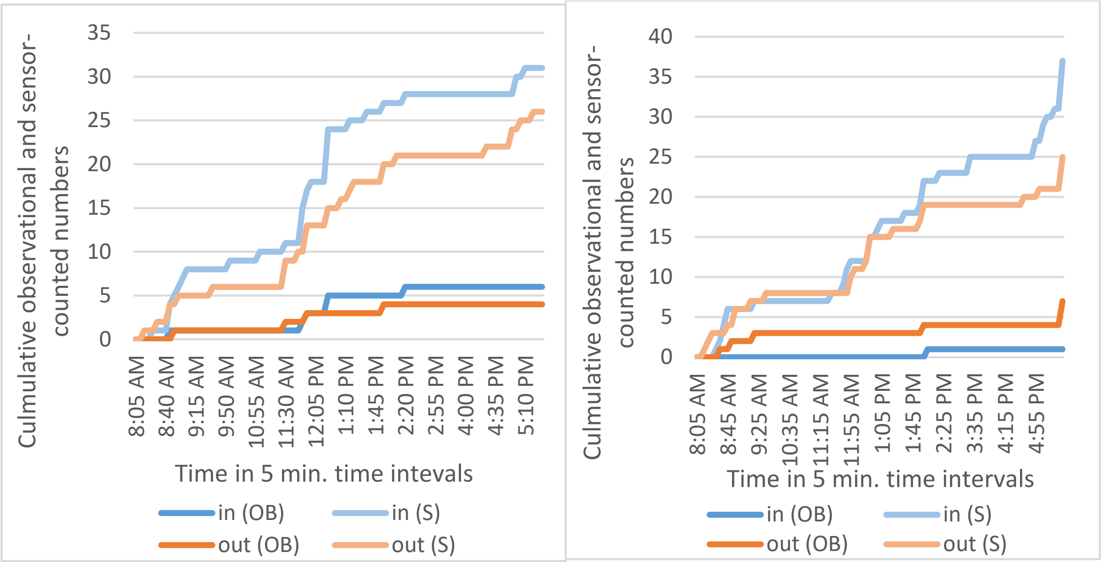


Figure 4.76 Comparisons of elevator sensor data and observational data in both directions after moving them to the second floor.

Here the E#1 sensor counted a total of 25 (417%) more people going in and 22 (550%) more people going out than the observer, while the E#2 sensor counted a total of 36 (3600%) more people going in and 18 (257%) more people going out than the observer. The second floor had less traffic than the ground floor and fewer people would be using the elevators daily based on the observations. However, the accuracy of the sensors was worse than when placed on the ground floor. The results were contradictory to our previous findings: the sensor was more accurate on the side doors than on the main door since less traffic was detected. A possible reason can be that the sensors were heavily disturbed by people’s movements on the second floor. The position of the elevators is close to the main entrance of the tenant’s office area on the second floor and most people would use this main corridor in front of the two elevators several times daily (without actually using the elevators). Those people were very likely to be recorded by the sensors but not by our observers, engendering an enormous difference in the two sets of numbers. The counts of people exiting the elevators were more accurate than the counts of people entering. A possible explanation is that when people enter the elevators, they may first have to wait a while for the elevators to arrive. This is obviously not the case when exiting the elevator. People’s movement while waiting can increase the sensor counts.

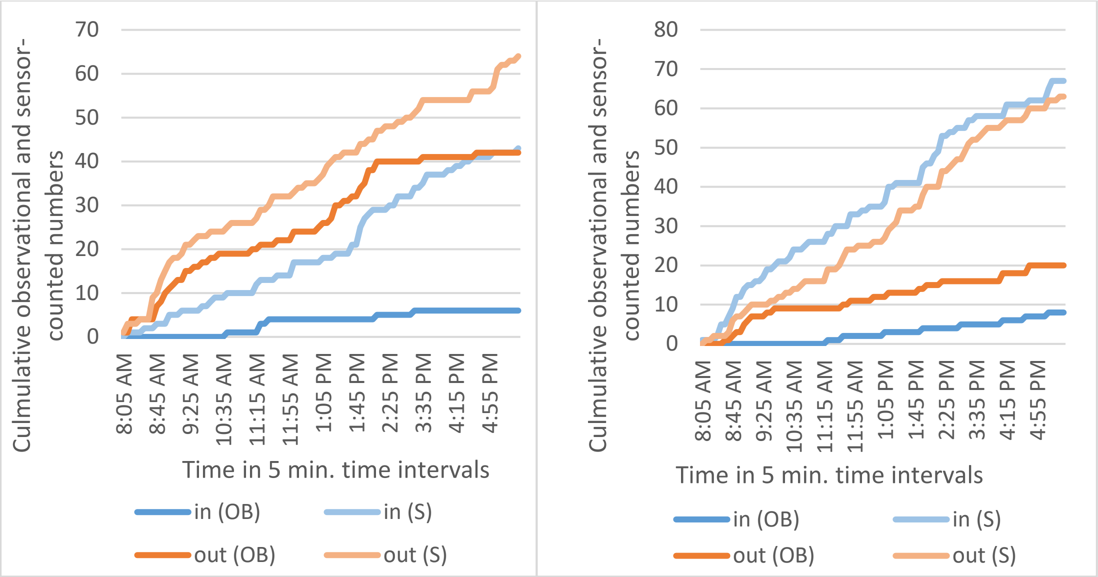


Figure 4.77 Comparisons of elevator sensor data and observational data in both directions after moving them to the third floor.

Here the E#1 sensor counted a total of 25 (617%) more people going in and 22 (52%) more people going out than the observation, while the sensor on the elevator #2 counted a total of 36 (738%) more people going in and 18 (215%) more people going out than the observer. Again, the overall accuracy was not improved by much compared to the second floor. One interesting finding was that the E#1 sensor was more accurate when counting people exiting the elevator. As identified in the previous graphs, sensor counts can be more accurate when people do not need to wait for the elevators to arrive. In this case, when the sensor was moved from the second floor to the third floor, more people were using elevators (as found in observations), and fewer people moving in front of the sensors meant fewer "disturbing factors". This can possibly explain the increase of accuracy in the directional counting.

| Test | Date | Sensor | Results compared to observation in (+/- %) | Results compared to observation out (+/- %) |
|---|---|---|---|---|
| Test 1: Center the sensors on the ground floor. | April 11th and 18th | E#1 | +32% | +48% |
| | | E#2 | +60% | +471% |

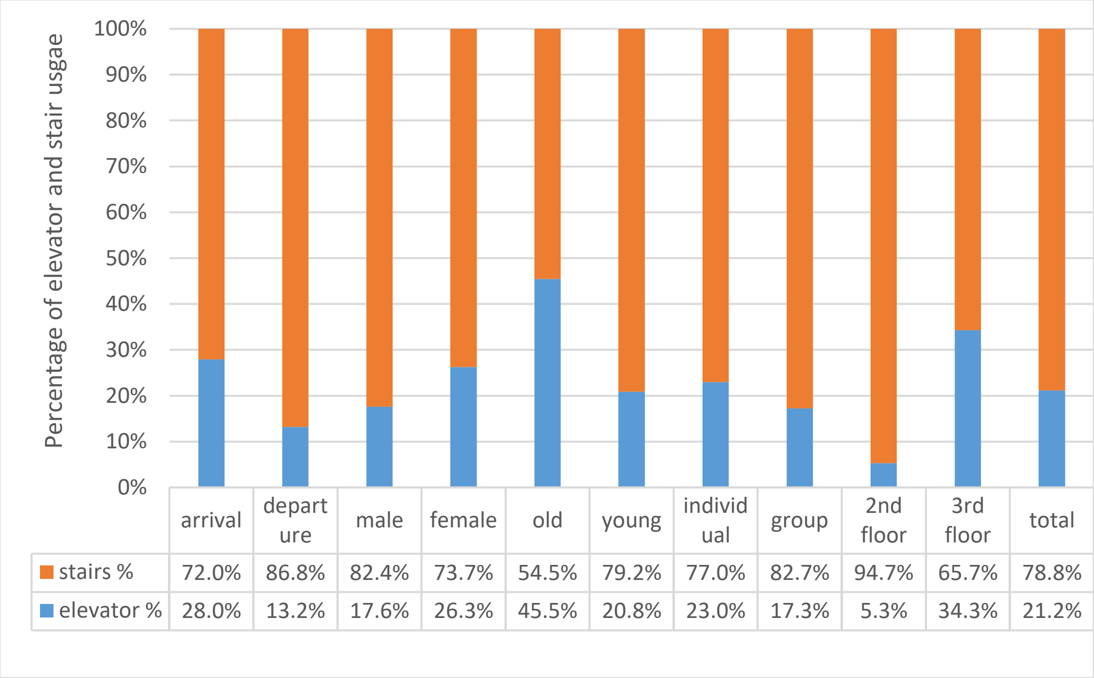
| | | | | |
|---|---|---|---|---|
| Test 2: Move the sensors to the side close to the wall. | May 1st | E#1 | -5% | +94% |
| | | E#2 | +28% | +165% |
| Test 3: Rotate the sensors inward by 30 degrees. | May 8th | E#1 | +30% | +71% |
| | | E#2 | +91% | +322% |
| Test 4: Move the adjusted sensors to the second floor. | May 15th | E#1 | +417% | +550% |
| | | E#2 | +3600% | +257% |
| Test 5: Move the adjusted sensors to the third floor. | May 22nd | E#1 | +617% | +52% |
| | | E#2 | +738% | +215% |

Table 4.4 Summary of the errors from sensors on elevators.

Elevator sensor error was in fact quite large in this study. In this case, the errors may not be amenable to data corrections. Combing the information from the observations and the counts reported from the sensors, the following factors can be identified as influencing the accuracy of the counts: First, the traffic flow of the corridor in front of the elevators. The more people move in front of the sensors the more like the sensors will be disturbed. Second, people’s waiting behaviors. The longer it took people to wait for the elevator to arrive, the more likely the sensors would be disturbed. Third, the movement of the elevator doors may disturb the sensors. However, the information gathered from the observations was not enough to help us identify the effectiveness of each potential effective factor (observers did not collect data about waiting time, total traffic including people who did not use elevators, etc.), and the sensor was not able to count the numbers precisely. Therefore, the radar sensor was not suitable as the sole source of data collection on elevator usage. In the next section, the stair and elevator usage baseline for the Evovl1 building was consequently established by using observational data.

### 4.2.11 Establishing the New Elevators-Stair Usage Baseline

Since the research introduced a new method (sensor-recording data) to study elevator and stair usage, the new elevator-stair usage baseline should be set up by using the sensor data which can cover all the stairs (both side and central stairs) and elevators. However, because the sensors on the elevators were inaccurate in collecting data (with the exception of the test 2 count of those entering elevator 1) and the errors cannot be adjusted by using available information at this stage, the baseline was established founded on the observational data and only covered the central stairs and elevators.



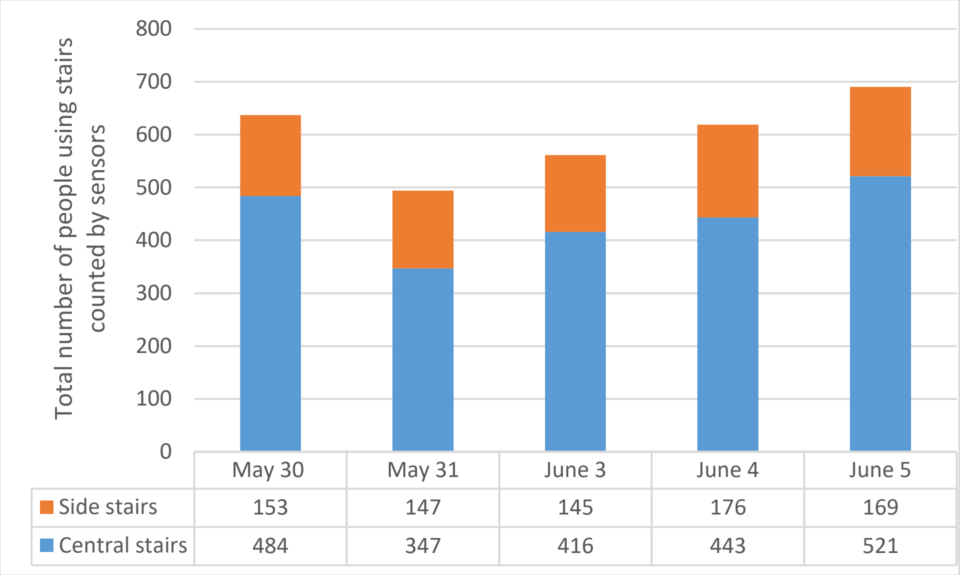
| | arrival | departure | male | female | old | young | individual | group | 2nd floor | 3rd floor | total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 🟧 stairs % | 72.0% | 86.8% | 82.4% | 73.7% | 54.5% | 79.2% | 77.0% | 82.7% | 94.7% | 65.7% | 78.8% |
| 🟦 elevator % | 28.0% | 13.2% | 17.6% | 26.3% | 45.5% | 20.8% | 23.0% | 17.3% | 5.3% | 34.3% | 21.2% |

Figure 4.78 The new elevator-stair usage percentage baseline for the building.

In Figure 4.78, baselines were calculated for the central stairs and elevators only (second/third floor central stairs). The data were from three days of observations: May 8th, May 15th, and May 22nd, when the elevator sensors were adjusted to their final orientations and positions.

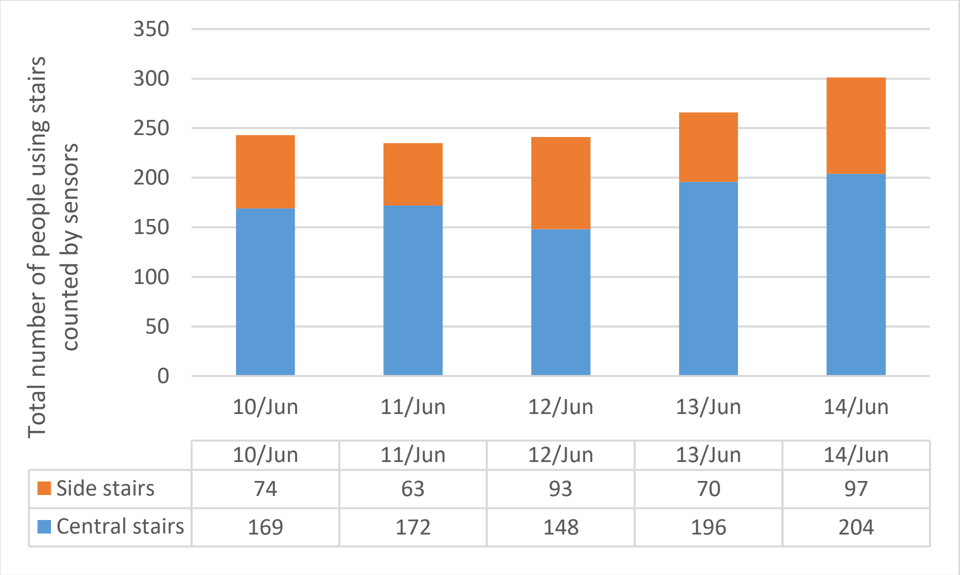
As shown, the overall stair usage rate was much higher than that of the elevators, and the second-floor stair usage rate (94.7%) was higher than that of the third floor (65.7%). In future research the side stair observational data should be added so that all the traffic in the Evovl1 building can be covered.

The data from elevator sensors were not accurate enough to be used for setting up baseline values. However, the sensors on stairs were relatively accurate and could be used to obtain stair usage amounts in the building.



| | May 30 | May 31 | June 3 | June 4 | June 5 |
|---|---|---|---|---|---|
| 🟧 Side stairs | 153 | 147 | 145 | 176 | 169 |
| 🟦 Central stairs | 484 | 347 | 416 | 443 | 521 |

Figure 4.79 Total number of people using stairs on second floor (counted by sensors).



| | 10/Jun | 11/Jun | 12/Jun | 13/Jun | 14/Jun |
|---|---|---|---|---|---|
| 🟧 Side stairs | 74 | 63 | 93 | 70 | 97 |
| 🟦 Central stairs | 169 | 172 | 148 | 196 | 204 |

Figure 4.80 Total number of people using stairs on third floor (counted by sensors).

The two figures show that the total number of people using stairs in the building was around 600 on the second floor and 257 on the third floor (averages calculated from the five day values). The results show that second-floor occupants use the stairs more than the third-floor occupants, which was consistent with previous findings.

### 4.2.12 Elevator Energy Consumption

The two elevators in the building were connected to a power panel which measured the total electrical consumption of all the connected circuits. The elevator was not the only circuit connected to it. However, when different numbers of people used the elevators, it was possible that the readings from the power panel would show the corresponding variations. Therefore, a regression analysis was performed between the number of people observed and the power consumption readings. The panel reported electricity consumption every 15 minutes while the number of people were counted every 5 minutes by observers. In the analysis, the time intervals for the observations were combined to be consistent with the 15-minute time intervals of panel reports. Therefore, not all the observational data were useable and data collected every 10 minutes would be excluded. In the graph below, the people counting data from March 5th, March 6th, April 11th, April 18th, May1st, and May 8th observations were used, and the corresponding energy data from the panel were collected for the regression.

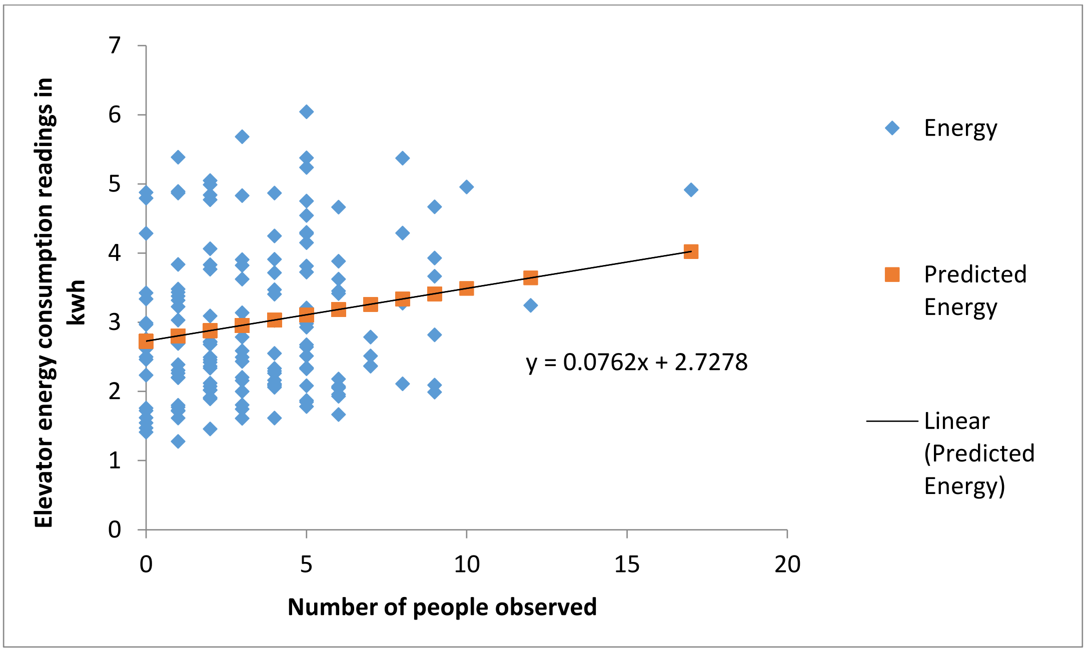


Figure 4.81 Regression plot for the elevator circuit energy consumption and the number of people observed.

The graph included 152 data points with 15-minute time intervals, and the regression was significant ($P = 0.017 < 0.05$). By using the linear regression equation, it can be roughly estimated that the elevator used 0.076 kWh of electricity per person using the elevator. This value can be used to calculate the annual energy consumption of people using elevators in the building.

In the next step, the time interval was increased to 30-minutes to retest the strength of the relationship between the two variables.

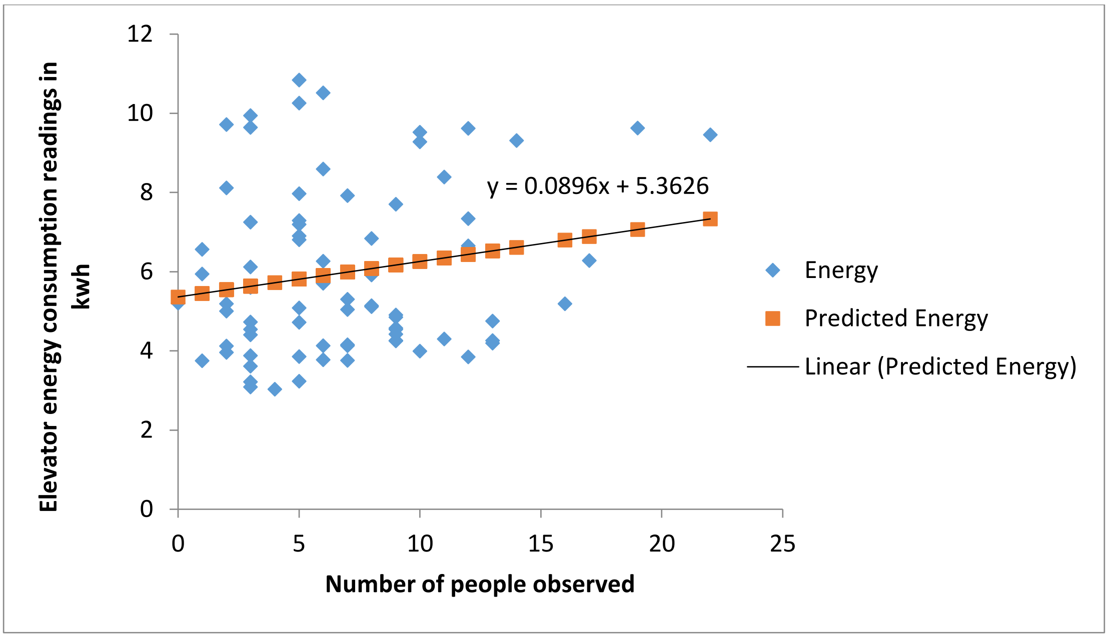


Figure 4.82 Regression plot for the elevator circuit energy consumption and the number of people observed

The graph included 76 data points with 30-minute time intervals, and the regression was not significant (P= 0.109 > 0.05). However, the slopes of the lines in the two graphs were very close to each other (0.0762 and 0.0896), indicating a similar increase in electricity consumption for each person using the elevator (76 vs 90 Wh). In addition, the y-intercept of the second linear relationship was twice as large as the first one (5.36 compared to 2.73), as would be expected by doubling the time interval. Consequently, the linear predictions were in fact consistent for estimating the relationship between energy consumption and the number of people using elevators. As the first equation included twice as many data points, it was suggested that its values be used to estimate the relationship (80 Wh/person). Another estimation was elevator energy consumption per trip travelled; that value was 115 Wh per trip. (Details displayed in Appendix D.)

# CHARPTER 5

# Discussion

## 5.1 New Energy and Emission Baselines

The estimated baseline value for the annual energy consumption of the tenants from the pre-occupancy stage was 1.14 GJ/m2, which was lower than both the 2016 averages of Canada (1.32 GJ/m2) and Ontario (1.39 GJ/m2). As was studied in previous literature, the Energy Use Index (EUI) of LEED gold buildings ranged from less than 63 kwh/m2 to more than 442 kwh/m2, (Geng et al., 2018) which can be converted to a GJ range from 0.23 GJ/m2 to 1.59 GJ/m2. Based on the design of the new building, its annual energy consumption was expected to be less than 100 kWh/m2 or 0.36 GJ/m2. Considering the renewable energy technologies used by the building (e.g. solar panels), the building can generate more energy annually than its consumption. The study by Diamond et al. showed that there were no correlations between actual energy performance and the different certification levels at the design stage. (Diamond et al., 2006) Furthermore, other studies have also shown that most of the LEED certified green buildings were less efficient than expected. (Council, U. G. B., 2009) The energy consumption data of the case study building in its operational phase is not yet available so the baseline values were only estimated values from the data of the pre-occupancy buildings. In the next stage of the research, utility data and meter data for the building will be used by researchers to measure the annual energy consumption and determine if the building meets its target.

The calculated pre-occupancy values for emissions were 32.9 kg CO2eq/m2 and 630 kg CO2eq/person at the tenants' previous buildings. These values were calculated based on the previous buildings occupied by the tenants, which used both natural gas and electricity. Since the new building uses only electricity and solar gains as its energy sources, the building would theoretically have "zero emissions" of GHGs when it operates. Therefore, the baseline numbers show the potential emission reduction that can be achieved by the tenants moving in.

However, the assessment could consider not only the emissions in the operational phase, but also those in the construction phase. Life cycle assessment methods were used frequently in previous research (Chau et al., 2015; Ma et al., 2017; Monahan &

Powell, 2011; Wu et al., 2017) in order to analyze the energy consumption and emissions throughout the building's entire life cycle. It would indeed also be interesting to see how much energy was consumed and emissions released during the construction phase of the new building. A related question is whether the energy-efficient equipment and designs resulted in increased embedded energy and emissions, and how long it will take for the building to offset these.

The results of elevators and stair usage baselines show that 70.0% people on the third floor and 81.5% people on the second floor choose to use stairs instead of elevators. Given the low-rise (three-floor) building design with a central staircase, it is not surprising that most people in the building chose stairs over elevators. However, as one of the important indicators of people's energy-saving behavior in the building, annual studies should be continued in order to see if improvements persist over time. The results from this research can be used as the baseline values of pre- and post-occupancy phases and can be compared to the results of future studies.

## 5.2 The Effective Factors for Elevator-Stair Behavior Changes

In the demographic analysis, one of the main findings was that young people in the building would be more likely (up to 33.4%) to use stairs than their elders. This result was consistent with the literature findings (Kerr & Carroll, 2001), however, the usage ratios were calculated based on different samples sizes. For example, in the post-occupancy stage observations, there were 567 counts of young people while only 17 counts of older people. Even though the research focused on the ratios instead of raw counts, the relatively small number of older people observed may indeed skew the results. For future research related to elevators and stair usage in other green buildings, the ratios of young/older people using elevators and stairs may be different due to different percentages of different groups of people. It will therefore be necessary to study the demographic patterns in different buildings specifically.

No significant differences were found in stair usage behaviors according to gender in this study. However, just like age, the different ratios of males/females on different floors may affect the result. (Details can be seen in Appendix E.) More data will be needed in order to ascertain the accurate ratio of ages and genders on each floor.

The analysis of direction of movement showed that people were more likely to take stairs when descending rather than ascending. Since going upstairs can be more tiring, these results were anticipated. In addition, the two-way ANOVA showed that there was no significant effect of interventions on the direction of movement data.

Concerning people moving in groups in comparison to people moving individually, statistically no evidence showed that their elevator/stair choices were different. However, the observers did note that a group of people was likely to move together. In other words, all the people in a group were very likely to make the same choice in terms of using elevators or stairs. Thus, similar individual and group choices indicate that stronger interventions or engagement plans should probably be carried out in order to build a culture of sustainability in the building.

The results also showed that people working on the second floor used the stairs more often than those on the third floor. One reason was that fewer stairs needed to be climbed. Furthermore, the company located on the second floor has a gym on the ground floor for its employees. Their employees consequently have (at least visual) encouragement to do a daily work out in the building, which may also lead them to exercise more by taking the stairs more often.

The findings above were mainly from the statistical results as well as the observations during the data collection. Additional studies may validate these initial findings. For example, future research can be done in a survey to ask about people’s awareness of building the culture of sustainability in the building, or if the gym affects their choice of using the stairs more often.

## 5.3 Effectiveness of Interventions

There were two main types of interventions considered in this project. The first was the prominent stair design of the building, and the second was the engagement workshops for the tenants in order to build a culture of sustainability. The analysis showed that differences in stair usage existed in the pre-occupancy stage among differently designed buildings. When tenants moved into the new building with a prominent central staircase, a significant increase of stair usage was observed, which can also be used as evidence that validates the effects of this design. As for the engagement plans and activities, there was also some effectiveness observed. However, from Figure 4.42, it is clear that stair usage fluctuated over time and most of the statistical tests that related to the interventions were not significant. The total number of participants engaged in sustainability workshops was small compared to the total number of people working in the building. Figure 4.78, 4.79, and 4.80 later included the data of the percentage of people using stairs on each of the floors in the case study building from observations and the total number of people using stairs from the sensor counts. By using these data, the estimated number of people on the second and third floors together was 255 (relying on the conservative assumption that each person traveled to and from the floor two times per day, details in Appendix F).

The details of the engagement plans/activities were provided by the staff of SWR. There were eight engagement activities arranged by the organization and by the end of the data collection of this study (mid-June), four of the eight engagement plans/activities had been carried out. The following are some details of these seven plans/activities manifesting their topics, dates, and number of people involved: 1. Engagement: Trivia Night where everyone gathered after work for popcorn and beer for a trivia night with some questions centered on sustainability, March 28th, 25 people; 2&3. Building: Technical building tours for citizens of the building, April 11th and April 15th, 22 and 17 people respectively; 4. Learning: DIY Living Wall Workshop with Ashley Demarte who designed and maintains the living wall, May 7th, 15 people. Other engagement plans that happened either after the data collection or have not happened yet: 5. Wellness: Vegetarian Cooking Class with Dr. Manuel Riemer where everyone gathered in the kitchen to learn how to make fresh vegetable rolls, July 10th, 18 people. 6. Wellness: Meditation classes run by an employee from one of the tenants, planned for Aug 22nd. 7. Community: Developing a community garden, date not decided. 8. Engagement: games night and BBQ, date not decided. Based on the information, these engagement activities promote ‘general effects’ rather than ‘specific effects’ since there were no activities that mentioned the use of elevators and stairs directly. However, their effectiveness may not be minor since some of the activities such as Trivia Night and building tours may in fact have mentioned some information about the work done for the elevators and stairs (e.g. central stair design, sensors for research purposes). In addition, the maximum size of 25 people attending each activity or workshop accounts for less than ten percent of the population on the higher floors, since some participants came from the first floor. This also limited the effectiveness of the interventions.

In future research, more specific interventions can be designed for stair/elevator - usage behaviors. Based on the literature review, stair usage is not solely a pro-environment behavior, it is also closely related to people's lifestyles and health. The research team can consequently try to use health motivations in order to engage the tenants, instead of using the energy-saving motivation alone. In the co-investigator meeting of the research members, methods such as using signs and posters to encourage people to use stairs were proposed. It will in fact be necessary to engage a larger number of people in the building since the culture of sustainability aims at involving every one of the building citizens.

## 5.4 Elevator Electricity Consumption

Based on the electricity consumption data provided by the building owner, an estimated value of elevator electricity consumption per time per person was calculated. However, more measurements are necessary in order to calculate the efficiency of elevators more precisely. The electrical consumption data used for the analysis were aggregated since there were multiple circuits connected to the power panel. Therefore, the measured energy consumption of elevators was overestimated. The y intercept of the regression plot showed the estimated real-time electricity consumption (2.7 kwh/15 minutes) for the base load of all the devices connected to the same power panel, so the equation can be used to calculate the energy consumption of the elevator when in use by different numbers of people. Subsequent researchers may consider connecting elevators to a separate circuit directly connected to the power panel or install a separate electricity meter in order to get an accurate electrical consumption reading. As the elevators are closely related to both the tenant's stair usage behaviors and the energy consumption of the building, obtaining an energy efficiency label may bring positive changes to the research in both of these areas. The VDI 4707 energy efficiency label for elevators evaluates both stand-by and travel energy consumption of an elevator by considering the influences from the elevator's travel height, speed, load and usage frequency. (Association of German Engineers, 2007) Such a label can be helpful in identifying how efficient the elevators are if the corresponding data are collected. The elevator's height, speed, and load are fixed data, but the usage frequency is relatively difficult to identify. In this research, the frequency was identified by observation and the amount of data was limited by using only one observer. In future research, more observers can be used, for longer observation times in order to get a more accurate estimation of the usage frequency. In addition, other methods can be considered, such as installing video cameras or determining if sensor accuracy can be improved in order to obtain more exact and efficient people counting data. Furthermore, the energy efficiency labels for the elevators would deliver a certain amount of energy-related information to the people in the building. First, people would know roughly how much energy is consumed every time the elevators are used, while this same amount of energy could be saved if they used stairs instead. In addition, the label would be color coded and indicate the class of elevator from highest efficiency to lowest (“A” to “G”, green to red). If the energy efficiency class of the elevator in the building is good (e.g. “A”), then the label works like a colorful poster adding energy-saving elements to the building itself.

## 5.5 Applications of Sensors in Future Research

The radar sensor data collection method for the people-counting used in this research was one of the methods categorized as a device-free localization (DFL) system reviewed by Shukri and Kamarudin (2017). A DFL system means no device is attached to the targeted entity and number of sensors used should be dependent on the requirements (Shukri & Kamarudin, 2017). The radar sensors were advantageous during the data collection stage. First, the sensors work 24/7, making the study’s long term trends continuous data much easier to gather. Second, using radar sensors was time-saving and required much less manual work than observations. However, the sensor batteries lasted only 5 days, so recharging and replacing the batteries created some additional work. The most important factor to consider was that the accuracy of the radar sensors was not ideal, based on the results of the analysis, especially for elevator-mounted sensors. Errors ranging up to 3600% can be considered as “very bad” for a measuring tool. In this case, researchers in future studies may need to find alternative ways to adjust the accuracy of these sensors before using them for data collection. Researchers are working on solutions to see if there are better ways to make use of the sensors (e.g. better orientations of the sensors on the elevator). The low accuracy of the radar sensor can possibly be the main reason why few previous researchers have used radar sensors alone in their studies when collecting people-counting data. However, there are many other researches using sensors which can achieve much greater accuracy when counting people. Choi et al. (2017) used so-called impulse radio ultra-wideband (IR-UWB) radar sensors for people counting when they passed through a path in two directions. This radar sensor is bigger than the PCR2 sensor, and must be mounted higher on the ceiling or pillar. The IR-UWB radar sensors are equipped with antennas which have a narrow beam width to form two invisible electronic layers in the path, so they can detect when multiple people pass in front of them. Overall, these sensors achieved an error less than 10% (Choi et al., 2017). Likewise, in 2017, Mohammadmoradi et al. did research by using IR Array sensors to count the number of people going through a doorway or the occupants in a certain room. The approach was simple, not expensive and reached an overall accuracy of 93% in identifying the number of people in a room (Mohammadmoradi et al., 2017). Future researchers may considering using better sensors or methods.

## 5.6 Limitations

This research was conducted during the first year of a five-year project, so many limitations of this research are identified and discussed below.

One of the main purposes of this research was establishing the energy and emission baselines of the new building by using the corresponding data from the tenants' previous buildings before they moved into the new zero carbon building. However, the data were not available for all the tenants because some of them did not share their previous energy and emission data with the research group. The baseline analysis was therefore not able to include all the tenants. Furthermore, most of the tenants who provided their energy and emission data cohabited their previous office buildings with other organizations instead of occupying the entire building. These organizations also shared the building's total energy use and emissions with the other occupants of the previous buildings. Since the research only collected building level energy and emission data, these building level data were used as the energy consumption and emissions of these tenants, thereby overestimating their values. The building level data of tenants from university campuses can hardly be found, so the energy/emission averages for the entire campuses were used to estimate their values. Since the campus probably also includes energy-intensive labs and machines, using these values can also overestimate the energy consumption and emissions of the university tenants. Another non-negligible factor was that each of the tenants employed a different number of people working/studying daily in the new building, so a weighted average by population could better estimate the baselines. However, researchers did not acquire the necessary information about how many people each organization/institution employed in the case study building by the end of the data collection.

In this study, it was difficult to collect accurate energy and emission data for the benchmark for each of the tenants. Since the data source and data quality were limited, the estimated baseline value is not very accurate. However, since all the tenants from the commercial buildings were previously in typical office buildings, the energy and emission values don’t have large variations, meaning that our estimated values are valid in representing the pre-occupancy level.

The second focus of this research was to study the elevator and stair usage of the tenants in the case study building. This part required observations to do primary data collections, so more limitations were identified. For the pre-occupancy research stage, two to three observers were used to do the observations in the tenants’ previous buildings. Limited by the number of available observers and different building designs (e.g. positions and number of stairs and elevators), the observations may not be able to cover all the stairs and elevators at the same time. The observers can only cover a certain number of elevator and stair locations at any one time. Elevator usage of all the buildings was observed, but stairs blocked by walls or doors were not counted. The total number of people that were not counted was in fact small (about 10 people at most for one day’s observation) but still, the aggregated pre-occupancy stair and elevator usage ratio (stairs over elevators) was slightly smaller than the actual usage ratio. The post-occupancy and post-engagement stage observations were performed by one or two people, so only the central elevator and the central stair usage was observed while usage of the two side stairs was not. The side stair usage data were all collected by subsequent people counting sensors, so the data were not missed.

One of the main limitations of the sensor collected data in the building was that the number of sensors was insufficient to cover all the building traffic at the same time. Four people counting sensors were used in the research, but the building has three stairs and two elevators in total. Researchers consequently had to rotate these sensors to different locations in order to cover all the traffic, and the data used to calculate the stair/elevator usage ratios may not be from the same day. Although the regression tests showed that the number of people using stairs and elevators was not significantly different day by day, this can still be regarded as a limitation of our data collection method. Another factor which considerably limited the research method was the accuracy of these sensors. Based on the comparisons of the observational data and the sensor-reporting data during the same time interval, it was found that the sensors are indeed error-prone and the two sets of data did not match well. Corrections were applied to the sensor-reporting data, however, since only one observer was available, these corrections were calculated based on one single day or two single days' data. The values of the corrections may therefore not be very accurate.

The limitations of this research were largely due to the limited number of observers and the poor quality of certain data. Since this research project will continue for four more years, the research team may consider hiring more observers for future research and use better sensor data collection equipment in the future.

# CHARPTER 6

## Summary

This study focused on the energy/emission performance and people's behaviors in a selected case study building, which served for a case study representing zero carbon green office buildings. The research can be separated in two parts: first, setting up the energy/emission baselines for the case study building; second, studying tenants' behavior changes by researching elevator and stair usage. The literature review gave an overall appreciation of several related ideas: the evolution of building science, development of building policy, transitional trends from traditional energy to clean energy sources, and the opportunities brought about by net-zero buildings in solving environmental problems. Specific fields of study directly consequential to the research were also examined. Previous research interests and findings were collected and then used for our own research design.

There were 7 tenants in the building and their previous office buildings were of different building designs and energy/carbon footprints. Methods were established separately for the two different parts of the research. Only secondary data were used when calculating the energy/emission baselines, and these data were mainly from the tenants' self-reporting (e.g. annual reports). Energy and emission baselines were computed from the previous office buildings both per person and per floor area, and a weighted average value was used as the baseline value for the case study building. The annual energy consumption was calculated to be 1.35 GJ/m2 and the emissions were calculated at 31.0 kgCO2eq/m2. The weighted averages per person were not calculated since the number of people for each tenant (i.e. employer) cannot be precisely estimated. The research design of this part was mainly limited by the availability and precision of data (e.g. some tenants did not provide their data; for campuses only campus-level data were available instead of building-level data.)

In terms of people's behavior changes, this research focused on studying the changes in people's use of stairs and elevators in different stages: pre-occupancy, post-occupancy, and post-engagement stages. For pre-occupancy and post-occupancy stages, only observational data were used for the analysis, while the post-occupancy stage allowed both observational and sensor-recorded data. However, the accuracy of the radar sensors used in data collection for this research was problematic when it came to the elevators, so only stair-sensor data were used for the baseline analysis. From the observations, the research identified that a central-staircase building design can engender more stair usage than a design with side stairs only, and higher floor height decreases the number of people using the stairs. In addition, the demographic analysis showed that young people use stairs more often than their elders, and people prefer stairs over elevators more often when descending. However, the engagement plans carried out in the case study building did not significantly improve people's stair-usage behaviors. This can be due to the fact that the total number of people who attended the activities/workshops was quite small compared to the total number of people in the Evovl1 building. The main limitations in this part of research design were from the small data sample size (only 1-3 people did the observations over a limited number of days) and the inaccuracy of the sensors.

In conclusion, the zero carbon building showed great potential in energy and emission reductions and also had some effects on changing peoples' behaviors. However, in future research better equipment should be used (e.g. better functional sensors) for the data collection and employing more observers would allow obtaining more accurate data and larger sample sizes for the analysis.

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# APPENDIX A – BATTERY RECHARGING SCHEDULE

Sample battery recharging schedule used in the case study building during the data collection of this research.

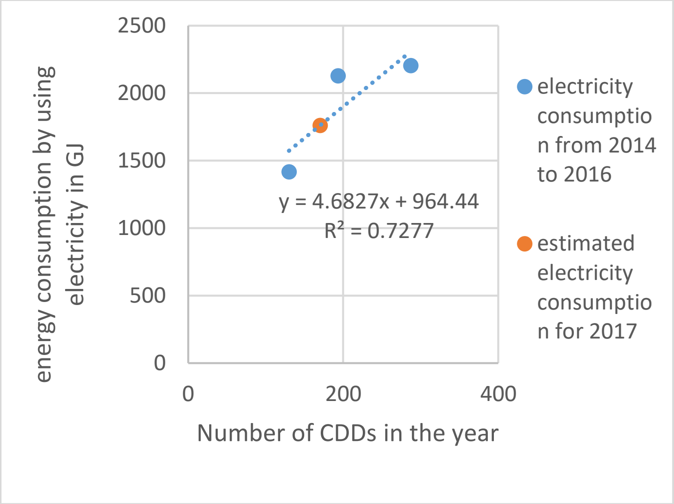
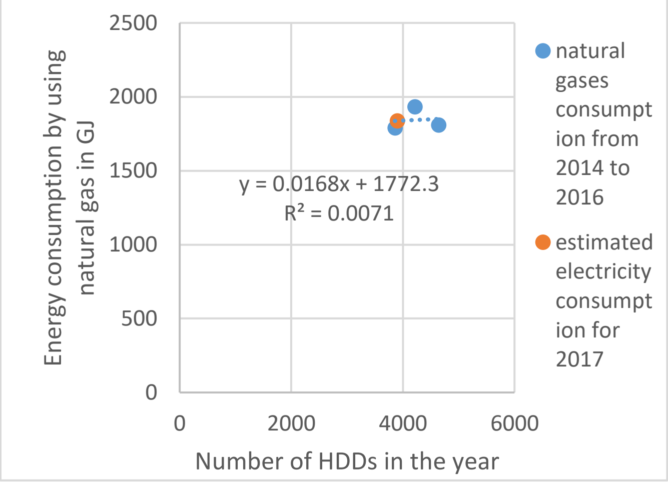
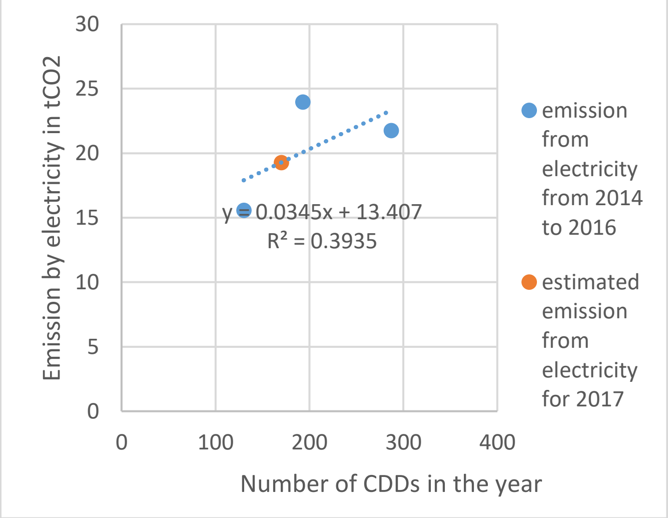
| | Battery power left at day's end (5 to 1) | | | |
|---|---|---|---|---|
| Date of the week | elevator sensor #1 | elevator sensor #2 | stair sensor # 1 | stair sensor #2 |
| Monday | 5 | 5 | 5 | 5 |
| Wednesday | 5 | 3 | 5 | 3 |
| Friday | 3 | 5 | 3 | 5 |
| Monday | 5 | 2 | 5 | 2 |
| Wednesday | 3 | 5 | 3 | 5 |
| Friday | 5 | 3 | 5 | 3 |

Table 1. Sample battery recharging schedule.

The numbers indicated the power remaining in each of the batteries, from 5 to 1 (highest to lowest). Each of the batteries can run for about 5 days if fully charged. In the schedule, all the batteries were fully charged at the beginning, and the first Wednesday the batteries of elevator sensor #1 and stair sensor #1 were replaced by fully charged extra batteries, so their power level was still 5. The two batteries taken out from these two sensors were sent to be recharged. Then, on Friday, the other two sensors' batteries were replaced by the fully charged batteries in the previous step and the cycle continued.

# APPENDIX B – ENERGY/EMISSION CALCULATION

Calculations for the 2017 energy/emission data of building 8.

| Relationships | Regression test results | Figures |
|---|---|---|
| Electricity energy consumption and CDDs | P = 0.349 > 0.05 Relationship not significant |  |
| Natural gas energy consumption and HDDs | P = 0.946 > 0.05 Relationship not significant |  |
| Emission from electricity and CDDs | P = 0.568 > 0.05 Relationship not significant |  |

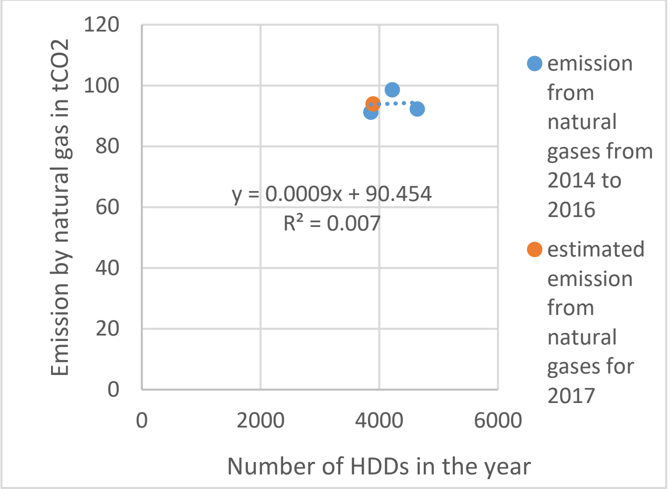
| | | |
|---|---|---|
| Emission from natural gas and HDDs | P = 0.947 > 0.05 Relationship not significant |  |

Table 2. Estimated energy consumption and emission for the TechTown building, 2017. The 2014 to 2016 energy/emission data were used for the estimation. Since none of the regression tests showed significant results, the trend lines were used to estimate the values. In total, the energy consumption of the TechTown building in 2017 = electricity energy + natural gas energy = 1760.499 GJ + 1837.8 GJ = 3598.3 GJ; the emissions from the TechTown building in 2017 = emission from electricity use + emission from natural gas use = 19.272 tCO2 + 93.96 t CO2 = 113.2 t CO2.

# APPENDIX C – SPACE CALCULATION

Space of each tenant in the new zero-carbon building.

| Tenant | Space (m2) |
|---|---|
| Tenant 1 | 590 |
| Tenant 2 | 3886 |
| Tenant 3 | 1220 |
| Tenant 4 | 230 |
| TN1 | 1080 |
| TN2 | 149 |
| TN3 | 2417.5 |

Table 3. Summary of floor area of each tenant.

Tenants 1 to 4 are marked consistent with the analysis in the body of the text, and other tenants with no energy/emission data available are marked as TN1 to TN3 (Tenant with No Data)

# APPENDIX D – ENERGY CONSUMPTION OF ELEVATORS BY TRIPS

A regression of the elevator energy consumption on the number of trips travelled was run as below.

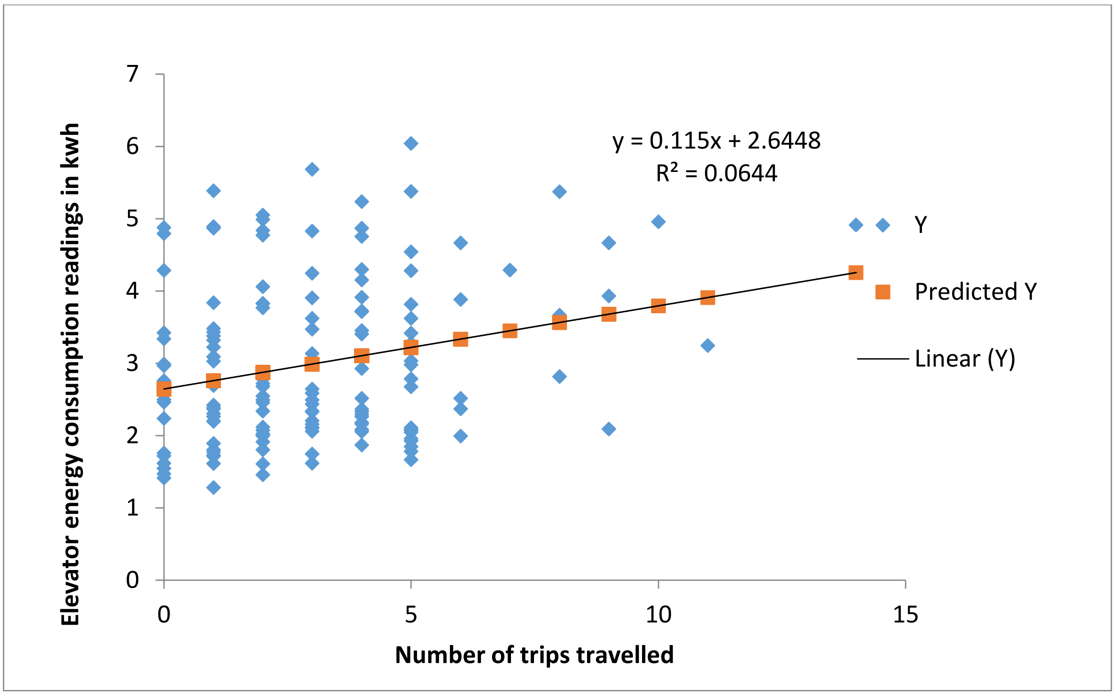


Figure 1. Regression plot of elevator energy consumption on number of trips travelled. The figure shows that the energy consumption of an elevator in the building was 0.115 kWh per trip travelled.

# APPENDIX E – DEMOGRAPHIC CALCULATION

Number of people of different ages and genders on the second and third floor of the case study building.

| | Second floor | third floor |
|---|---|---|
| male | 134 (70.9%) | 98 (48.0%) |
| female | 55 (29.1%) | 106 (52.0%) |
| young | 189 (100.0%) | 201 (98.5%) |
| older | 0 (0.0%) | 3 (1.5%) |

Table 4. Number (and percentage) of people in different demographic groups in each floor of the case study building.

As shown in the table, the ratios of young and older people on each floor was very unbalanced. In addition, males considerably outnumbered females on the second floor.

# APPENDIX F – POPULATION CALCULATION

An estimation of number of people on each floor of the case study building based on the data gathered in Figures 78, 79, and 80. The number of people on each floor of the building can be estimated by using the total number of people using stairs and the percentage of stair usage on each floor.

On second floor, the average count of number of people using stairs daily was 600, and the percentage of stair usage was 94.7%, so the total count of number of people travelling to/from second floor was 600/94.7% = 633 (rounded down)

On the third floor, the total count of number of people travelling to/from the floor was 257/65.7% = 391 (rounded down)

If we assume that each person travelled to and from the floor one time per day (coming to work and going home), then the numbers should be divided by 2, so the number of people would be 316 on the second floor and 195 on the third floor (both numbers rounded down). If we also assume that each person travelled to and from the floor two times per day (leaving and returning during the lunch break as well), then the numbers should be divided by 4, so the numbers would be 158 on the second floor and 97 on the third floor.