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Interrelations between Greenhouse Gas (GHG) Emission and Total Floor Area of Buildings -With the Case Study of Public Facilities in Ontario, Canada-

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Abstract Recently, it is becoming increasingly difficult to ignore carbon emission implication of building operations due to the significant rate of energy usage in buildings. In the building sector, our normal expectation implies that large building floor area induces more greenhouse gas (GHG) emission. In this research, the correlation between building total floor areas and GHG emission was explored by simple linear regression and analyzing the yielded residuals for confirming this seemingly obvious conjecture. By looking at the generated regression lines drawn based on the data sets representing public facilities in Ontario, Canada, we were able to confirm that carbon emission rate shows a proportional increase or decrease depending on the total floor area of buildings as has been implied as a conjecture. Some buildings were found to emit significantly large and small amount of GHG, and we addressed potential reasons why those buildings show the deviation from the confirmed proportional interrelation between a building's total floor area and the amount of GHG emission.

Keywords: Greenhouse Gas, Building Area, Simple Linear Regression, Residual Analysis

1. INTRODUCTION

Up to now, the generation of energy in the world is seriously relied on conventional fossil fuels and many studies have predicted that the world's oil reserves are very likely to be finished in 35~60 years (The Colorado River Commission of Nevada, 2002). Thus, the heavy dependence on the conventional energy sources such as fossil fuels is a critical issue given that for instance, approximately 40 per cent of the total U.S. energy consumption is dedicated to maintaining buildings (Pérez-Lombard and Ortiz, 2008). Due to increasing energy usage in building sector, it is becoming increasingly difficult to ignore the carbon emission implication of energy usage as well. As we know, gases that trap heat in the Earth's atmosphere are called greenhouse gases (GHGs). Carbon dioxide, methane, nitrous oxide, and fluorinated gases are GHGs. Mostly, carbon dioxide makes a majority in all GHGs, and 81 per cent of entire GHG emissions in 2014 in the United States is carbon dioxide (U.S. Environmental Protection Agency, n.d). In the building sector, it is a sort of a conjecture that large building floor induces more GHG emission. To confirm this conjecture, in this study, the correlation between building total floor area and GHG emission was explicated by drawing regression line; the same kind of correlation was also pursued between building types and GHG emission. The regression lines drawn with the public building cases in Ontario, Canada would be expected to clarify this correlation except some special cases showing significantly large and small amount of GHG that need extra explanations on the reasons why such buildings reveal greater or lower GHG emission tendency.

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2. BACKGROUND AND RELATED WORKS

To give a useful direction for reducing GHG emissions, Meinshausen et al. (2009) stated that more than 100 countries have adopted a global warming limit of 2 °C or below as a

Table 1. Summarized statistics of the two building groups' total floor area in square footage.

Building Type	Min.	1st Quartile	Median	Mean	3rd Quartile	Max.
Hospital	100	3,144	5,977	46,895	13,362	2,163,574
School	200	24,422	38,999	59,562	60,742	7,247,973

Table 2. Summarized statistics of two building groups' GHG emission (kg) calculated from 2011 to 2013.

Year	Building Type	Min.	1st Quartile	Median	Mean	3rd Quartile	Max.
2011	Hospital	250	11,636	25,099	396,369	54,734	17,349,426
	School	216	63,705	99,024	177,220	159,633	39,940,761
2012	Hospital	5	9,837	22,038	396,068	52,752	17,655,396
	School	299	69,549	108,061	186,880	171,890	38,382,911
2013	Hospital	19	13,692	34,539	564,164	92,543	27,808,774
	School	35	101,999	170,874	306,811	268,314	37,368,611

guiding principle for mitigation efforts to reduce climate change risks, impacts, and damages. However, the GHG emissions corresponding to a specified maximum warming are poorly known owing to uncertainties in the carbon cycle and the climate response. According to a study by Pérez-Lombard, Ortiz, and Pout (2008), the global energy consumption for buildings, both residential and commercial, has steadily increased by 20 per cent to 40 per cent in developed countries. With a growing world population, building energy demand will increase more and more, and thus designing and operating energy efficient buildings becomes a critical issue globally not just energy issue alone but the GHG emission that causes climate change and global warming. Micro climate condition of the sites, functional types and total floor area of buildings are considered to be major independent variables impacting on the energy and GHG emission profiles of buildings. This study paid attention to the correlation between total floor area of buildings and GHG emission rate which normally has been considered to be obvious without systematic investigation with real-world data sets for confirmation. We used the accessible data sets of public facilities (medical and educational facilities) in Ontario, Canada to show a generic approach for identifying targeted correlation that we are interested in.

3. METHOD FOR CORRELATION IDENTIFICATION

Simple linear regression concerns two-dimensional sample points with one independent variable and one dependent variable and finds a linear function that predicts the dependent variable values as a function of the independent variables. Simple linear regression modelling techniques can be used to investigate how the two variables, corresponding to the data values x_i and y_i are related. In this paper, x_i represents the total building floor area in square feet, and y_i represents GHG emission of the i^{th} building in each type of building. (Hayter, 2013)

In particular, the simple linear regression model can be expressed as

$$y_i = \beta_0 + \beta_1 x_i + \varepsilon_i \tag{1}$$

The expected value of the dependent variable is modeled as a linear function of the values of the explanatory variables. The unknown parameters which determine the relationship between the dependent variable and the explanatory variable, can be estimated from the data set. In addition, a third unknown parameter, the error variance σ^2 , can be guess from the data set (2013). In addition to the simple linear regression, the residuals are defined to be

$$e_i = y_i - \hat{y}_i, \qquad 1 \le i \le n \tag{2}$$

and there are differences between the observed values of the dependent variable y_i and the corresponding fitted values . A property of these residuals is that they sum to 0 (2013).

Analysis on the residuals is a useful way of checking whether the fitted model is credible and the assumptions made for modeling appear valid or not. A basic residual analysis technique for the simple linear regression problem is to plot the residuals e_i against the values of the explanatory variable x_i (2013).

4. PERFORMED EXPERIMENT

(1) Description of the Data Sets

The Environmental Commissioner of Ontario in Canada investigated greenhouse gas (GHG) emissions of almost 15,000 different public sector buildings starting from 2011 until 2013 including schools, hospitals, recreational centers, and municipal

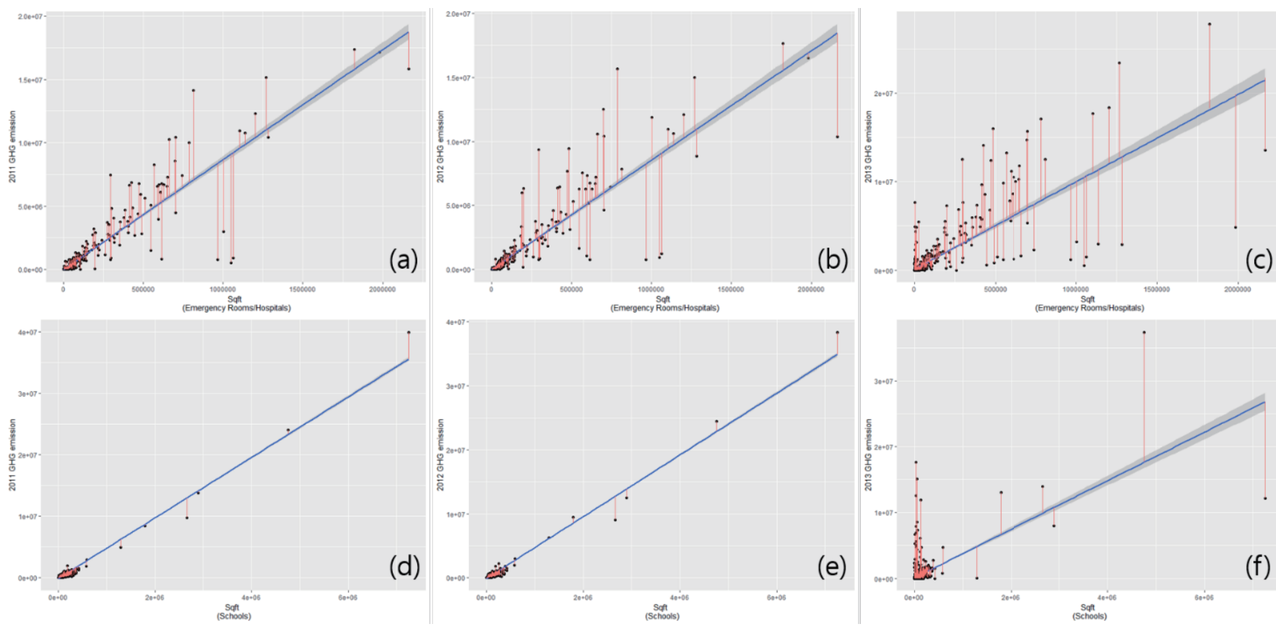

Figure 1. (a) Building area vs. GHG emission(Hospitals, 2011), (b) Building area vs. GHG emission(Hospitals, 2012), (c) Building area vs. GHG emission(Hospitals, 2013), (d) Building area vs. GHG emission(Schools, 2011), (e) Building area vs. GHG emission(Schools, 2012), (f) Building area vs. GHG emission(Schools, 2013).

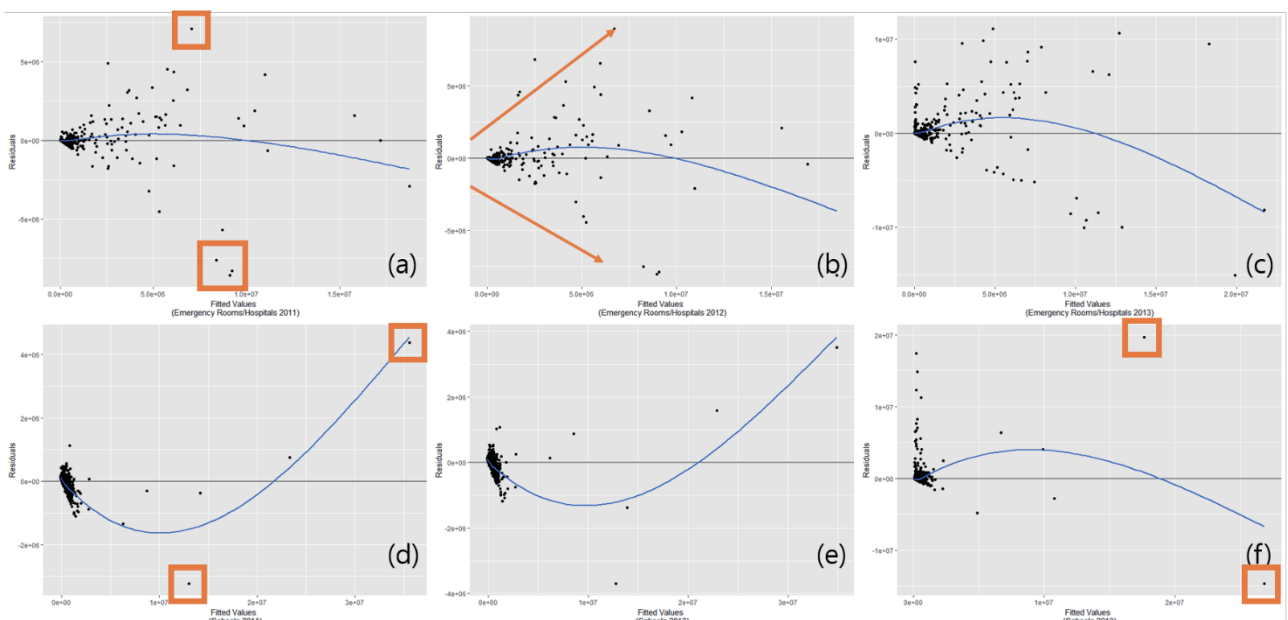

Figure 2. (a) Residuals in regression anlysis (Hospitals, 2011), (b) Residuals in regression anlysis (Hospitals, 2012), (c) Residuals in regression anlysis (Hospitals, 2013), (d) Residuals in regression anlysis (Schools, 2011), (e) Residuals in regression anlysis (Schools, 2012), (f) Residuals in regression anlysis (Schools, 2013).

buildings. This data set includes not only GHG emission data, but also the types of public facilities, total building floor areas in square feet, the amount of energy cost savings compared with the year 2011 counted in Canadian dollars, the amount of energy savings in equivalent kilowatt per hours as well as the site coordinate information (Environmental Commissioner of Ontario, 2016). The data set has been recognized as valuable information in terms of investigating all the public buildings in Ontario, Canada.

From the accessed data set, building types and total floor areas of public facilities (hospital group and school group) and corresponding GHG emissions of selected buildings for the period of 2011 - 2013 were extracted. The software tool utilized to perform needed statistical analysis was R which is built for statistical computing and graphics. Using R, we plotted graphs and calculated linear fitted regression. The total number of tested buildings was 5,268 out of approximately 15,000. 1,255 hospital buildings and 4,013 school buildings were selected for the analysis.

Table 1 shows total building floor areas of the selected hospitals ranged from 100 to 2,163,574 square feet. Schools also showed a wide range of total building floor area profile varying from 200 to 7,247,973 square feet. Table 2 shows the two groups' GHG emission variation ranges examined from 2011 to 2013.

(2) Case Study with Selected Data Sets

With the prepared data set, the interrelation between total building floor areas and the corresponding GHG emissions analyzed from 2011 to 2013 is presented in Figure 1. The equations below show the correlation between the total building floor area of each building type and corresponding GHG emission in 2011. Each equation has a 0 value of y-intercept with their own slopes. The regression lines were drawn according to the equations.

x_1, x_3, and x_5 : Total building floor areas of hospitals

y_1 : Year 2011 GHG emissions from hospitals

y_3 : Year 2012 GHG emissions from hospitals

y_5 : Year 2013 GHG emissions from hospitals

$$y_1 = -10817.615 + 8.683x_1 \quad (3)$$

$$y_3 = -4293.923 + 8.537x_3 \quad (4)$$

$$y_5 = 100700 + 9.883x_5 \quad (5)$$

x_2, x_4, and : Total building floor areas of schools

y_2 : Year 2011 GHG emissions from schools

y_4 : Year 2012 GHG emissions from schools

y_6 : Year 2013 GHG emissions from schools

$$y_2 = -1.160 * 10^5 + 4.6923x_2 \quad (6)$$

$$y_4 = -1.006 * 10^5 + 4.827x_4 \quad (7)$$

$$y_6 = 87173.288 + 3.688x_6 \quad (8)$$

In Figure 1, the regression lines are represented by blue lines and red lines show residuals of each building. As for the graphs representing two different building groups, all simple regression lines had positive slope, which means that GHG emissions in 2011 increased as the building size increased. The hospitals group showed higher slope value (3) than that of the schools group (6). Within the school building group, most of the target buildings were forming a unilaterally clustered group except for a few buildings.

As for 2012 GHG emission profiles, the slope value for the emergency and hospital group was 8.531, which marked the highest value among the entire building groups examined (4), nevertheless, the slope value in 2012 was lower than the slope value in 2011 (3). With the school building group, the graph representing the year 2012 is similar to the graph in 2011. A few buildings deviated from the clustered majority group.

With the year 2013 GHG emission profile, the regression slope of the hospital building group was also lower than that of the previous years. As for the school building group, the clustered points spread out more, and some of the buildings consumed more energy than previous years. However, one huge building emitted much less GHGs in 2013, and we would mention about this special building case in the later part.

Some data points shown in the residual plots in Figure 2 are outliers. In particular, some points inside orange boxes on the graphs can be considered as outliers in this data set. If the residual graph shows a "funnel shape", the size of the residuals depends upon the value of the explanatory variable x, and the assumption of a constant error variance σ^2 is not valid. In fact, the fitted regression line and statistical inferences still give genuinely sensible outcomes regardless of whether there is some variation in the error variance, in spite of the fact that a more exact investigation might be accessible using a weighted minimum squares approach.

The residual graphs for hospitals have the funnel shape and this shape indicates as orange colored arrows. As can be seen from Figure 2-(a) and 2-(d), which shows residuals from the regression lines between total building floor area and GHG emissions in 2011, some outliers can be seen again from the residual plots in Figure 2-(c) and 2-(f). Notably, points inside orange boxes on the graphs can be considered to be outliers in this data set. In this study, we would try to find what the outliers represent, and what buildings they are. In other words, those outliers would be the buildings showing the largest amount of GHGs emitted.

5. RESULTS

From the residuals of regression analysis for each type of building, three of the buildings showed largest residuals and three of the ones revealed smallest residuals were selected. The buildings that showed the large residuals in regression outcome consumed more energy thus emitted more GHGs compared with the identified typical GHG emission pattern that is proportionate to the total building floor areas. Meanwhile, the buildings that marked the small residuals in regression analysis consumed less energy and emitted less GHGs compared with the majority of other buildings in the same group.

With the hospital building group, Joint Justice Facility showed the first lowest GHG emissions in 2011, the second lowest GHG emissions in 2012, and the second lowest GHG emissions in 2013. Since this building was reconstructed in 2001, providing a full rain-screen that seals all air and vapor, and thick walls that spans total 320mm. With this structure, this building could greatly reduce energy consumption as well as GHG emission every year. By contrast, the three buildings emitting larger amount of GHG in 2011, 2012 and 2013 are all different. Investigating why they showed such differences is a potential topic for further exploration.

As for the school building group, Queen's University (Campus total) emitted the largest amount of GHGs in 2011 and 2012. However, there was a sudden change in 2013. Queen's University became the campus with the lowest GHG emissions in 2013. In fact, starting in January 2012, Queen's University launched a climate action plan to reduce their GHG emissions. Conversely, in terms of Carleton University's GHG emission profile, it showed the second highest emission rate in 2011, then it gradually increased until Carleton University emitted the largest amount of GHGs in 2013. Carleton's student body has grown by 18% over the last 10 years, and the number of students in residence has increased by 32%. For those reasons, the school's GHG emission level increased gradually.

6. CONCLUSION

Within the building sector, anyone would expect that large total building floor area induces more GHG emission. In this study, we confirmed this conjecture by performing a simple linear regression analysis and determining the residuals; the results showed that total building floor area, in fact, has a strong correlation with GHG emissions.

The findings revealed in this research could be used in the following fashion. Firstly, identified correlation regression graphs for certain group of buildings differentiated by their location, function or size attributes could form specific signatures of the chosen groups that represent generic tendencies of GHG emission. This type of signature graphs can provide a basis for predicting GHG emission performance of a certain building, checking a building's deviation from average GHG emission level of the other buildings in the same group, or GHG emission increase/decrease with temporal changes due to remodeling or deterioration instances. Secondly, slopes of the regression lines for each building group represents the magnitude of GHG emission due to the chosen (i.e. Total building floor area) building attribute or even depending on the sub-groups in the same building group. For instance, Hospital building group in our study showed higher slope in the regression graph compared to that of school building group. As a matter of fact, a simple regression analysis presented in this study could give us the way of identifying approximately quantifiable GHG emission profiles of a certain groups of buildings classified by their unique attribute.

The general public would also be interested in the relationship between building's GHG emission and local weather condition or the interrelation between the building's GHG emission and occupancy type. However, this study is limited in that various building objects included in the Canadian survey were not possessing necessary profiles and conditions to cover those additional regression analysis targets. Therefore, weather profile of building sites and occupancy types could be considered in the further research.

Moreover, a quadratic or higher degree of equation might be used to analyze the target data sets. In this case, we would see the points where the regression lines, calculated for various building types, meet and what the total building floor area is at that point, which would give more information for the optimum design and operation of buildings in different context and size.

Even though we relied on Canadian public building related data sets for our correlational analysis on building size and GHG emission presented in this study, the same method and process could be used to examine similar relationships for providing insightful building design and operational guideline to reduce GHG emission in domestic building sector while maximizing cost and energy efficiency of various types of buildings.

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