ENERGY PERFORMANCE BENCHMARK MODEL FOR AIRPORT TERMINAL BUILDINGS

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ABSTRACT

This paper presents a methodology for an Energy Use Intensity (EUI) benchmark for Airport Terminal Buildings (ATBs) based on the analysis of utility bills, simulation results, and regression modeling. Buildings consume more than 40% of the total energy in the US, and ATBs are one of the largest energy consuming building types. A methodology was developed utilizing standardized factors and EUI_{ATB} normalization from both measured and simulated data. The energy performance benchmark model for ATBs was tested for the effectiveness of evaluating the energy performance of existing and future ATBs, and is discussed here.

INTRODUCTION

A U.S. Department of Energy (USDOE) survey of energy consumption levels of buildings showed that buildings in the U.S. accounted for about 41% of total energy consumption in 2010 (USDOE, 2015). This amount was 44% more than the transportation sector and 36% more than the industrial sector. Moreover, the U.S. building sector accounted for 7% of global primary energy consumption in 2010 (USDOE, 2015), with commercial buildings covering about 46% of total building energy consumption (USDOE, 2015).

For the analysis of building energy performance, most energy analysts use EUI (kBtu/sf-yr: annual energy use divided by total building area) to measure energy consumption levels relative to the building’s gross area (AIA, 2012). For example, if a 10,000 sf (929 m^2) office consumes 900,000 kBtu (263,763 kWh) of energy a year, the building EUI would be 90 kBtu/sf-yr (283.92 kWh/m^2-yr as a SI unit).

The Commercial Buildings Energy Consumption Survey (CBECS) report by the U.S. Energy Information Administration (USEIA) is a frequently used as a benchmark. Acording to the CBECS report, major commercial buildings are categorized as 14 types: education, food sales, food service, health care, lodging, retail, office, public assembly, public order and safety, religious worship, service, warehouse and storage, other, and vacant (USEIA, 2008). By using measured energy use data and building area, CBECS report indicates EUIs of the 14 building types such as 83.1 kBtu/sf-yr (262.2 kWh/m^2-yr) of Education and 100 kBtu/sf-yr (315.5 kWh/m^2-yr) of Lodging, and so on.

However, some building types are not included in the CBECS report, AIA guide, and other energy performance studies. Among the types, ATBs are one of the largest energy consuming buildings and one of the largest-scaled building complexes. Many designers and engineers do not clearly refer to ATBs EUI baseline due to a lack of information. Therefore, it is necessary to develop a methodology or metric to measure the level of energy performance of ATBs.

AIRPORT TERMINAL BUILDINGS

ATBs consist of multiple building (space) types in one structure, such as office, retail, mall, Food Service (FS), Public Order and Safety (PO&S), Public Assembly (PA), and other support areas. Energy consumption patterns of ATBs are complicated due to the complexity of space types and operational characteristics. The Clean Airport Partnership (CAP) along with the Stantec architectural service company in Edmonton provided the EUIs of 10 and 12 actual ATBs in North and Central America. According to the reports, Ronald Reagan Washington National consumed about 320 kBtu/sf-yr, but Salt Lake City Intternational consumed 150 kBtu/sf-yr (CAP, 2003). Dallas Fort Worth International consumed 178 kBtu/sf-yr, while Los Angeles World consumed 206 kBtu/sf-yr (Stantec, 2012). Even though the reports did not provide any clear patterns of energy consumption, we can conclude that the EUI variations are due to factors such as the characteristics of building geometry, building (space) types, operation, and the various business models of each ATB. Additionally, the composition of building (space) types of ATBs should be analyzed to define the characteristics.

The Transportation Research Board (TRB) summarized the building (space) types of ATB; i.e., ticketing/check-in, passenger screening, baggage claim/handling, holdroom (departure lounge), concession, office/operation area, support area, and circulation (TRB, 2010). Stantec performed 12 airport projects and defined the building (space) types of ATB: office, concession retail & food, baggage handling & screening, general passenger area, vacant space, and additional area. ATBs' space types were defined based on the information available from the reports of Stantec, TRB and CBECS, as shown in Table 1.

Table 1 Space Types and Share of ATB Space

Iden No.	Building (space) type categorization by Stantec	Building (space) type categorization by CBECS	Typical Share of ATB Space
1	Office Space	Office	15%
2	Concessions - Retail, Food	Retail, Food Service	5%
3	Baggage Handling & Screening	Public Order & Safety	10%
4	General Passenger Areas (Check-in, Arrivals, Waiting areas, Washrooms, etc.)	Public Assembly	28%
5	Vacant Space (Currently Unoccupied)	Other	2%
6	Additional Areas (Corridors, Storage, etc.)	Other	40%
	Total		100%

(Stantec, 2012; TRB, 2010; USEIA, 2008)

Of the six building (space) types, ticketing/check-in, baggage handling & screening, and holdroom areas should satisfy the strict regulations and specific requirements of Federal Aviation Administration (FAA), International Air Transportation Association (IATA), and International Civil Aviation Organization (ICAO). Two of the six spaces types, which are office and concession area, occupy about 20% of total floor area, and they have great potential to reduce energy consumption due to flexibility during design and planning. To increase the accuracy of a benchmark model, the layout of ATB space is used with the analysis of observed (or measured) EUIs of existing ATBs in CAP report, Stantec report, and the observed EUIs of office, retail, and FS in CBECS report.

ENERGY BENCHMARK

Energy benchmark methodologies for commercial buildings have already been established. Some authors in early studies developed adjusted and modified regression models called "package", but they commonly suggested the simple regression model as a baseline for the developed benchmark models. The simple regression model was given as

$$EUI = a + b_1x_1^* + b_2x_2^* + \ldots + b_kx_k^* + \varepsilon \qquad (1)$$

where, "a" is an intercept, "$b_1,\ldots,b_k$" are regression coefficient, "$x_1^*,\ldots x_k^*$" are significant standardized factors, ε is random error

(Monts & Blissett, 1982; Nie, Hull, Jenkins, Steinbrenner, & Brent, 1975; Sharp, 1996)

If we know the mean EUI of certain building types (intercept a), regression coefficients of factors ($b_1,\ldots,b_k$), and standardized values of factors ($x_1^*,\ldots x_k^*$), we can evaluate the observed EUI of existing buildings or predict the EUI level of future buildings through the Eq. (1).

Chung et al. (2006) pointed out that previous studies used the simple mean EUI as the intercept "a" without reflecting the normalization of possible factors. The simple mean of EUI may cause statistical problems because of insufficient population numbers and because of the complexity of planning ATBs. For the normalization of EUI, authors derived a modified equation from Eq. (1). They let the observed EUI be the EUI_0, the intercept "a" be the EUI_{norm}, $\{b_1,\ldots,b_k\}$ be the regression coefficients, and $\{x_1^*,\ldots x_k^*\}$ be the standardized factors. Then, the equation for normalized EUI (EUI_{norm}) is given as

$$EUI_{norm} = EUI_0 - b_1x_1^* - b_2x_2^* - \ldots - b_kx_k^* \qquad (2)$$

where EUI_0 is observed EUI, $b_1,\ldots,b_k$ are regression coefficient, $x_1^*,\ldots x_k^*$ are significant standardized factors (Chung, Hui, & Lam, 2006)

Based on the measured data of 30 supermarkets in Hong Kong, the authors calculated the regression coefficients and removed the insignificant factors by using the backward elimination method. As an example of final models, they suggested the equation with the selected significant factors: building age, floor area, operation schedule, number of customers, and occupants' behavior. The final equation model that the authors suggested is given as

$$\begin{aligned} EUI_{norm} = {} & EUI_0 - 972.6*(\text{building age} - 21.13)/11.29 + 1519.2*(\text{floor area} - 219.37)/175.76 \\ & - 588.4*(\text{operation schedule} - 7071.9)/1777.9 - 470.3*(\text{\# of customers} - 441350)/229057 + 411.5*(\text{occupants behavior} - 1.97)/1.73 \end{aligned} \qquad (3)$$

(Chung, Hui, & Lam, 2006).

In this paper, the Eq. (2) is developed by the analysis of ATB characteristics with the regression coefficients and the standardized values.

METHODOLOGY

Model of Normalized EUI of ATBs

The EUI of ATB (EUI_{ATB}) can be affected by various explanatory variables such as area, age, lighting, climate condition, enplanement, and other surveyed details. Among them, some variables are specified by building types in ATB, such as office area, but others are specified by the entire ATB such as enplanement. By using this simple regression model, a new formation of Eq. (2) is obtained.

$$\begin{aligned} EUI_{norm} &= EUI_0 - [b_1x_1^* + b_2x_2^* + \dots + b_kx_k^*] \\ &\quad - [c_1y_1^* + c_2y_2^* + \dots + c_ky_k^*] \\ &= EUI_0 - [\text{Sum of all impacts from explanatory variables (SUM) in ATB}] \\ &\quad - [\text{Sum of all impacts from explanatory variables (SUM) of ATB}] \end{aligned} \quad (4)$$

As indicated in Table 1, we define the shares of ATB space of office and concessions equals 15% (0.15) and 5% (0.05), respectively. Because concessions consist of retail and food service, we assume that the percentage is divided as 2.5% (0.025) and 2.5% (0.025). In the case of PO&S, PA, and others, energy consumption patterns are proportionally reflected in the observed EUI because they follow the strict regulation of FAA, IATA, and ICAO. It is assumed that PO&S, PA, and others do not have any significant effects as changed, so they can be neglected in the model. The [SUM in ATB] is given by

$$\begin{aligned} [\text{SUM in ATB}] &= 0.15^*[\text{SUM of office}] + 0.05^*[\text{SUM of concession}] \\ &= 0.15^*[\text{SUM of office}] + 0.025^*[\text{SUM of retail}] + 0.025^*[\text{SUM of FS}] \end{aligned} \quad (5)$$

From the Eq. (4) and (5), adjusted normalized EUI model for ATBs is obtained:

$$\begin{aligned} EUI_{norm} &= EUI_0 - 0.15^*[\text{SUM of office}] \\ &\quad - 0.025^*[\text{SUM of retail}] - 0.025^*[\text{SUM of FS}] \\ &\quad - [\text{SUM of ATB}] \end{aligned} \quad (6)$$

where, EUI_0 is the observed EUI, [SUM of office] is $(c_1u_1^* + c_2u_2^* + \dots + c_ku_k^*)$, [SUM of retail] is $(d_1v_1^* + d_2v_2^* + \dots + d_kv_k^*)$, [SUM of FS] is $(e_1w_1^* + e_2w_2^* + \dots + e_kw_k^*)$, [SUM of ATB] is $(f_1x_1^* +, \dots, f_kx_k^*)$.

This process does not use the absolute amount of energy consumption of each building type, but instead calculates how each factor affects change to the EUI of existing ATBs. Energy consumption of offices and commercial areas in ATBs are already applied to measure EUI in specific zones. Because the purpose of our model is to define average affects of factors, all CBECS and simulation data is applied as a standardization value: offices and commercial areas are operated as standard zones. In our process, all existing commercial building types are used to cover a wide range of variation from CBECS as well as theoretical types from simulation. Eq. (6) is finalized after the analysis of impacts of explanatory variables from the measured and simulated data.

Explanatory Variables

From the raw data of CBECS report, office, retail, and FS building types are filtered by the explanatory variables: building area (Area), building age (Age), number of business (Business), number of occupants (Occupant), electricity used for lighting (Lighting), number of interior equipment or electricity used for interior equipment (Equip), Heating Degree Days (HDD), and Cooling Degree Days (CDD). From the 27 Offices (Haberl, 2001), Area, HDD, and CDD are used to define the significance. The 20 ATBs by CAP and Stantec reports are used to analyze the affects of Area, Enplanement, HDD, and CDD.

Most measured data includes unexpected outliers and random errors. To validate and complement them, 90 EnergyPlus simulations are performed. Table 2 indicates the simulation conditions, templates, and parameters used.

Table 2 Simulation Conditions and Templates Used

No.	Building Type	Office, Retail, Food Service
1	Location	2009 IECC 7 Climate Zones (random selection)
2	Area	5,000~50,000sf (random selection)
3	Number of Story	1~5 (random selection)
4	Building Age	4~22 (based on EnergyPlus construction set)
5	Number of Business	1~6 (random selection)
6	Number of Occupant	EnergyPlus default template
7	Lighting	EnergyPlus default template
8	Equipment	EnergyPlus default template
9	HDD	USDOE weather file
10	CDD	USDOE weather file

The raw data of explanatory variables is then standardized to remove the effect of deviance out of each different scale. Finally, with the standardized data (as data on X axis) and their EUIs (as data on Y axis), scatter plots of each variable are generated. Based on these steps, we obtained 52 total sets of table and scatter plot.

Figure 1 describes the EUI distribution as the area of 30 offices from EnergyPlus simulation. Thirty simulations is the minimum number for statistical validation. The trend that the EUI decreases as office area increases is confirmed in Figure 1.

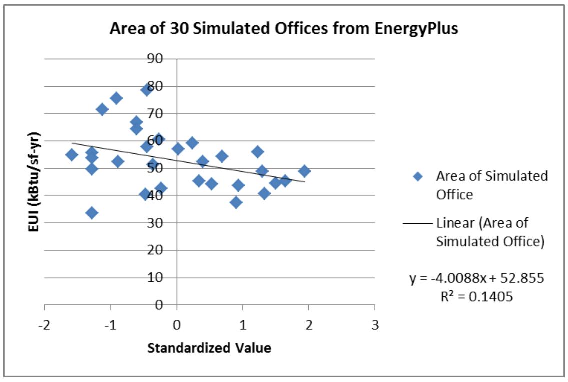

Figure 1 EUI Distribution as Area of 30 Simulated Offices from EnergyPlus

For the low number of R^2, ANOVA test will additionally be performed to define strength or weakness of relationship between EUI and each explanatory variable. As compared to Figure 1, the R^2 of retail's age in Figure 2 is quite larger than the office area. The wide range of variances of data points is seen, so significance validation is required.

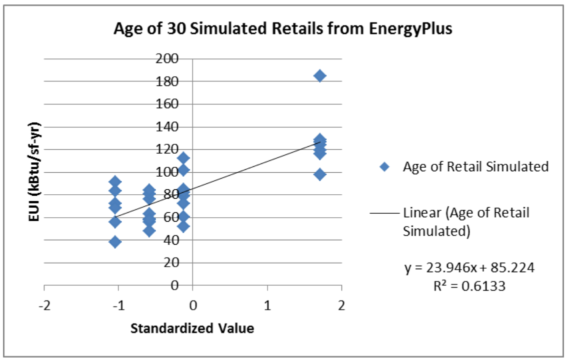

Figure 2 EUI Distribution as Age of 30 Simulated Retails from EnergyPlus

Figure 3 describes the EUI distribution as the HDD of 355 measured retails from CBECS report. We cannot clearly define the relationship between EUI and HDD even though the slope is calculated; it may be caused by outliers within the large sample size.

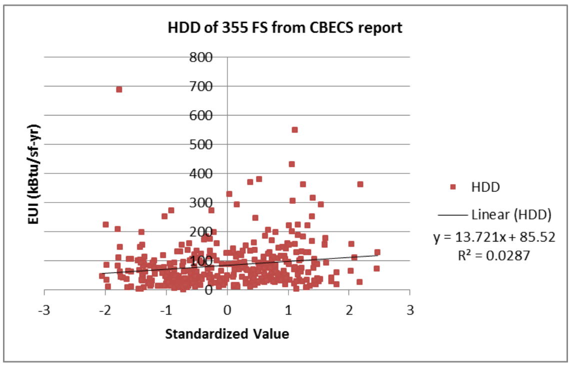

Figure 3 EUI Distribution as HDD of 355 Measured Offices from CBECS Report

Some points in Figure 3, such as 691 kBtu/sf-yr and 562 kBtu/sf-yr, could affect the result as a noticeable outlier. According to CBECS report, the two surveyed buildings have relatively small floor areas (5,000 sf and 7,900 sf) but quite large electricity use for cooling (449,987 MBtu and 215,712 MBtu). Statistical validation process is required to nullify the effect of outliers and clarify the significance. For further study, a more rigorous statistical method could be applied to reduce the effects of outliers.

For another example, Figure 4 describes the EUI distribution as the enplanement of 20 measured ATBs from the CAP and Stantec reports. The effect of enplanement can be larger than the area because the absolute value of the regression coefficient is about two times larger than the area. However, the data distribution of enplanement also shows an unclear trend as compared to the area. For this reason, all explanatory variables should be statistically analyzed.

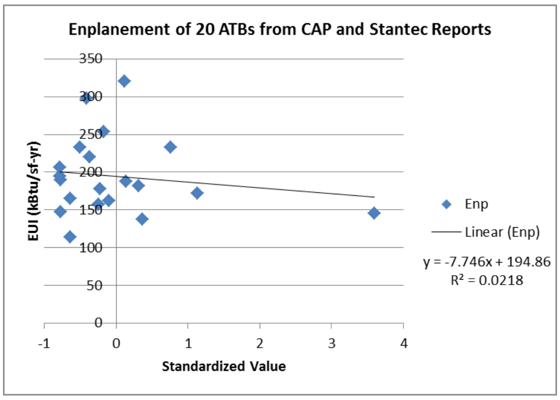

Figure 4 EUI Distribution as Enplanement of 20 Measured ATBs from CAP and Stantec Reports

From the 52 sets of table and scatter plot, the regression coefficients of all explanatory variables and their respective significances are defined by the p-values of ANOVA test through the SPSS program.

RESULTS

Analysis of Explanatory Variables

Some scattered plot data distributions show different patterns and slopes for the same explanatory variables or building (space) types. Table 3 shows the results of regression coefficients and the p-values (significance) of the relationship between EUIs and explanatory variables. The p-values less than 0.05 show a strong relationship between the EUI (dependent variable) and explanatory variables in ANOVA test. The 10 statistically significant variables are highlighted.

The p-values of the number of businesses and the number of occupants show no significant relationships between them and the EUI change; therefore, they can be removed as significant factors in the [SUM in ATB].

According to the study of E Source Companies, lighting accounts for 27%~43% of end use energy consumption in office buildings (E Source Companies LLC., 2010). However, even though 3 p-values for lighting in Table 3 are relatively more significant than the other explanatory variables, the statistical interpretation describes the lighting as an insignificant factor in office (p-value is 0.132>0.05) and FS (p-value is 0.276>0.05). On the other hand, lighting in retail is a significant factor (p-value is 0.005<0.05). Lighting is generally regarded as a critical factor of building electricity consumption, but variations of other factors in this model decrease the effect of lighting. In this simulation, the hypothesis that lighting does not proportionally change EUI due to synthetic effects of area, age, equipment, climate condition, and so on is confirmed. Likewise, the amount of interior equipment is also a significant factor (p-value is 0.006<0.05) in office, but not in retail and FS.

Total ATB area and enplanement in 20 airports are confirmed as insignificant factors as explanatory variables, so they can be ignored in Eq. (6). For further study, more observed data of total ATB area and enplanement is required because the data collected is insufficient to make a precise and strict statistical interpretation.

In general, higher CDDs and HDDs contribute to increased EUI in a building. However, due to higher temperature differences between outdoor and indoor room temperature, heating requires more energy than cooling in most climate zones. For instance, in summer, cooling energy operates to decrease temperature from 80~100ºF to 75~78ºF, but, in winter, heating energy operates to increase temperature from 0~40ºF to 68~75ºF. This difference makes the heating load more critical than the cooling load in most zones with four distinct seasons. In the case of office and retail, EUIs are increasing as the number of HDD is increasing in simulated and CBECS data. Because heating energy consumption directly affects EUI by increasing it, the regression coefficients of office and retail show the larger positive number. The FS shows the insignificant negative number of the regression coefficient, which may be caused by factors specific to FS, such as kitchen and dining area equipment as heating sources.

As CDD is increasing, the EUI of office and retail is decreasing. However, the p-values between simulated scenarios and the CBECS show relatively large differences. Therefore, more precise data collection is required to define these differences. The FS in CBECS shows totally different trends as compared to the office and retail. This result can explain that FS may have a different

No.	Factor	Building Type	Data Type	Regression Coefficient	p-value from ANOVA
1	Area	Office	Sim.	-4.0088	0.041
2			CBECS	3.1546	0.068
3		Retail	Sim.	1.8542	0.750
4			CBECS	-0.0890	0.984
5		FS	Sim.	3.7834	0.666
6			CBECS	-61.1340	0.001
7		27 Offices		-8.5526	0.395
8		22 Airports		-3.6753	0.757
9	Story	Office	Sim.	4.3319	0.026
10		Retail	Sim.	1.1342	0.846
11		FS	Sim.	4.4978	0.603
12	Age	Office	Sim.	-0.1381	0.946
13			CBECS	0.6221	0.719
14		Retail	Sim.	23.9460	0.000
15			CBECS	-6.8020	0.114
16		FS	Sim.	18.2420	0.028
17			CBECS	-76.7390	0.000
18	Business	Office	Sim.	2.6727	0.183
19			CBECS	-2.5285	0.146
20		Retail	Sim.	-0.8611	0.883
21			CBECS	0.2790	0.948
22		FS	Sim.	-2.8694	0.740
23			CBECS	-31.0270	0.093
24	Occupant	Office	Sim.	-3.1300	0.117
25		Retail	Sim.	2.0159	0.729
26		FS	Sim.	3.4855	0.687
27	Lighting	Office	Sim.	-3.0077	0.132
28		Retail	Sim.	15.1460	0.005
29		FS	Sim.	9.3430	0.276
30	Equip	Office	Sim.	-3.3317	0.094
31			CBECS	4.7585	0.006
32		Retail	Sim.	8.7250	0.126
33			CBECS	3.0858	0.475
34		FS	Sim.	11.3320	0.184
35			CBECS	-5.8660	0.752
36	Enp	22 Airports		-3.0260	0.799
37	HDD	Office	Sim.	6.8344	0.000
38			CBECS	6.5645	0.000
39		Retail	Sim.	17.5090	0.001
40			CBECS	13.7210	0.001
41		FS	Sim.	-0.7885	0.927
42			CBECS	-21.2060	0.252
43		27 Offices		-15.1330	0.127
44		22 Airports		4.6768	0.694
45	CDD	Office	Sim.	-1.0246	0.615
46			CBECS	-4.5057	0.009
47		Retail	Sim.	-4.5149	0.436
48			CBECS	-2.8092	0.513
49		FS	Sim.	22.6470	0.005
50			CBECS	12.0670	0.515
51		27 Offices		15.8050	0.110
52		22 Airports		-7.1413	0.546

Table 3 *Coefficient and Significance (p-value) of Explanatory Variables*

business model in terms of number of customers, lighting, and equipment.

The energy consumption level of commercial buildings can be affected by various factors. Through the analysis of the regression coefficients and p-values, the significant explanatory variables are defined. The total 11 explanatory variables are defined as significant factors to be applied for the SUM of each building type in the final model.

Final Model of Normalized EUI of ATBs

From Table 3, the significant explanatory variables for the final model are defined: area for office & FS, age for retail & FS, lighting for retail, equipment for office, HDD for office & retail, and CDD for office & FS. With the explanatory variables defined, [SUM of office], [SUM of retail], and [SUM of FS] in Eq. (6) are defined and obtained.

$$\begin{gathered}[\text{SUM of office}]=R_{Area}*\text{S. of Area}_{Office}\\ +R_{Equip}*\text{S.of Equip}_{Office}+R_{HDD}*\text{S.of}\\ \text{HDD}_{Office}+R_{CDD}*\text{S.of CDD}_{Office}\\ =(-4.0088)*\text{S. of Area}_{Office}+4.7585*\text{S. of}\\ \text{Equip}_{Office}+6.6995*\text{S. of HDD}_{Office}\\ +(-4.5057)*\text{S. of CDD}_{Office}\end{gathered}\tag{7}$$

(Note that R is the regression coefficient, and S. is the standardized value)

Likewise, [SUM of retail] and [SUM of FS] are given by

$$\begin{gathered}[\text{SUM of retail}]=23.9460*\text{S. of Age}_{Retail}\\ +15.1460*\text{S. of Lighting}_{Retail}\\ +15.6150*\text{S. of HDD}_{Retail}\end{gathered}\tag{8}$$

$$\begin{gathered}[\text{SUM of FS}]=(-61.1340)*\text{S. of Area}_{FS}\\ +(-29.2485)*\text{S.of Age}_{FS}\\ +22.6470*\text{S. of CDD}_{FS}\end{gathered}\tag{9}$$

As previously mentioned, we cannot confirm any statistical significance between the EUI and total floor area, enplanement, and HDD & CDD of ATBs. Therefore, [SUM of ATB] as $(f_1x_1^* +,\ldots,f_kx_k^*)$ in Eq. (6) is removed.

From the Eq. (6), (7), (8), and (9), the final model of EUI_{norm} is obtained as an equation:

$$\begin{gathered}EUI_{norm}=EUI_0-0.15*\{(-4.0088)*\text{S. of}\\ \text{Area}_{Office}+4.7585*\text{S. of Equip}_{Office}\\ +6.6995*\text{S. of HDD}_{Office}+(-4.5057)*\text{S. of}\\ \text{CDD}_{Office}\}\\ -0.025*(23.9460*\text{S. of Age}_{Retail}+15.1460*\text{S.}\\ \text{of Lighting}_{Retail}+15.6150*\text{S. of HDD}_{Retail})\\ -0.025*\{(-61.1340)*\text{S. of Area}_{FS}\\ +(-29.2485)*\text{S. of Age}_{FS}+22.6470*\text{S. of}\\ \text{CDD}_{FS}\}\end{gathered}\tag{10}$$

The normalized EUIs from this final the model will be compared to the observed EUIs from CAP and Stantec reports. The difference between the two EUIs will explain the significance of the final model.

Case Study

A. General information at 2011 (CAP, 2003; FAA, 2015; Stantec, 2012)

1. Name: Dallas-Fort Worth International
2. Climate conditions
    a. Climate zone 2
    b. HDD65: 2,327
    c. CDD65: 2,759
3. Year built: 1973
4. Total floor area: 2,227,000 sf
5. Number of stories: 5
6. Annual enplanement: 27,518,358
7. Observed EUI: 178.00 kBtu/sf-yr

B. Program and operation detail (projected from the floor space share of Stantec report and the linear regression model of CBECS report)

1. Office
    a. Floor area: 334,050 sf
    b. Electricity used for lighting: 1,336.57 kBtu/h
    c. Number of interior equipment: 1,251.26
2. Retail
    a. Floor area: 55,675
    b. Electricity used for lighting: 450.34 kBtu/h
    c. Number of interior equipment: 24.40
3. Food Service
    a. Floor area: 55,675
    b. Electricity used for lighting: 320.74 kBtu/h
    c. Number of interior equipment: 13.63

By using the Eq. (10) and the standardized values of above information, the result of EUI_{norm} is obtained:

$$\begin{gathered}EUI_{norm}=178-0.15*\{(-4.0088)*(5.2704)\\ +4.7585*(0.4946)+6.6995*(-1.075)\\ +(-4.5057)*(5.368)\}\\ -0.025*\{23.9460*(3.2483)\\ +15.1460*(-1.8218)+15.6150*(-0.957)\}\\ -0.025*\{(-61.1340)*(2.3508)\\ +(-29.2485)*(-0.363)+22.6470*(3.5237)\}\\ =186.83\text{ kBtu/sf-yr }(589.39\text{ kWh/m}^2\text{-yr})\end{gathered}\tag{11}$$

Likewise, the normalized EUIs of 20 ATBs are obtained because two ATBs are duplicated in CAP and Stantec reports: Dallas-Fort Worth International and Salt Lake City International. Table 4 shows the observed and normalized EUIs of 20 ATBs. The Stantec report provided the EUI with no subdivision of electricity and natural gas consumption, so the total is used for observed EUI. In the case of the CAP report, the paper provided the subdivision of electricity and natural gas consumption. Additionally, only the numbers from a 6-month average were provided, so annual consumption was projected using the regression model from the 6-month average data. The observed EUIs of 8 ATBs (from the Hartsfield Jackson International to the Cincinnati-Northern Kentucky) consist of the sum of electricity consumed and projected natural gas consumption.

Comparison between observed and normalized EUI

Using the 20 ATBs normalized EUI calculations as a case study we can obtain each ATB's normalized EUIs and their mean. Table 4 shows these results.

Table 4 Observed and Normalized EUIs of 20 Airports

Ident No.	ATB Name	Observed EUI from the CAP and Stantec Report		Normalized EUI from the final model (Eq.10)	
		kBtu/sf-yr	kWh/m2-yr	kBtu/sf-yr	kWh/m2-yr
1	San Francisco Int'l, CA	172.00	542.60	185.00	583.60
2	Toronto Pearson, CAN	138.00	435.34	144.59	456.12
3	Salt Lake City Int'l, UT	188.00	593.08	191.91	605.40
4	Calgary Int'l, CAN	254.00	801.29	256.45	809.00
5	Dallas Fort Worth Int'l, TX	178.00	561.53	186.83	589.39
6	Kamloops, CAN	157.00	495.28	161.45	509.32
7	Nassau Int'l, BAHAMAS	114.00	359.63	119.41	376.70
8	Sangster Int'l, JAMAICA	165.00	520.52	171.99	542.59
9	Hamilton, CAN	147.00	463.74	144.73	456.59
10	Cranbrook, CAN	190.00	599.39	186.16	587.28
11	Fort St. Johns, CAN	195.00	615.16	190.27	600.24
12	Los Angeles World, CA	206.00	649.86	207.07	653.22
13	Hartsfield Jackson Int'l, GA	145.57	459.22	154.86	488.52
14	Seattle-Tacoma Int'l, WA	233.04	735.16	239.40	755.24
15	Fort Lauderdale-Hollywood Int'l, FL	181.72	573.27	170.03	536.39
16	Ronald Reagan Washington National, VA	320.30	1010.44	322.88	1018.56
17	Portland Int'l, OR	162.55	512.79	166.20	524.31
18	Cleveland Hopkins Int'l, OH	219.68	693.02	222.75	702.69
19	Pittsburgh Int'l, PA	297.68	939.08	302.74	955.04
20	Cincinnati-Northern Kentucky Int'l, KY	232.68	734.03	238.22	751.50
	Average	194.86	614.72	198.15	625.09

Each EUI_{ATB} shows various patterns. The three largest ATBs in the table, San Francisco (SFO), Toronto Pearson (YYZ), and Hartsfield Jackson (ATL), show relatively low EUI numbers, but the three smallest ATBs, Cranbrook (YXC), Fort St. Johns (YXJ), and Los Angeles World (LAWA) consume relatively more energy. However, Dallas-Fort Worth (DFW) and Seattle-Tacoma (SEA) consume more than some small ATBs, even though they are each relatively large-scaled.

The values of the normalized EUI column show results from Eq. (10) calculations. While the observed EUIs of large-scaled ATBs such as SFO, ATL, DFW, and YYZ increased, the EUI of small ATBs such as Hamilton, Cranbrook, Fort St. Johns, and Fort Lauderdale-Hollywood International (these 4 ATBs are highlighted in Table 4) are relatively decreased after the normalization process.

As indicated in the average, the simple mean of observed EUI_{ATB} is 194.86kBtu/sf-yr, and the mean of normalized EUI_{ATB} is 198.15 kBtu/sf-yr. The observed EUI_{ATB} is about 1.63% lower than the normalized EUI_{ATB}. All of the normalized EUIs from the 20 ATBs can be used to define the more precise and realistic mean EUI of actual ATBs.

CONCLUSION

In this paper, the energy performance benchmark model for ATBs is developed using the information of actual database and simulation results. The share of ATB space devoted to each building (space) types defines the influence of it. The analysis of datasets and scatter plots of explanatory variables defines the regression coefficients, which may affect ATB performance. The final model for normalized EUI_{ATB} is obtained by using this analysis, and the result can then be used to compare observed EUI_{ATB}.

The case study and Table 4 confirm the simple mean of measured EUI_{ATB} to be 194.86 kBtu/sf-yr and the mean of normalized EUI_{ATB} to be 198.15 kBtu/sf-yr. This result proves that the mean of observed EUI_{ATB} is 1.63% lower than the mean of normalized EUI_{ATB} after the process. The mean of observed EUI_{ATB} is precisely adjusted through the geometric analysis and operational conditions of 20 ATBs. The 198.15kBtu/sf-yr from the mean of normalized EUI_{ATB} can be utilized as a precise baseline for ATBs such as 92.9 kBtu/sf-yr for office and 187.9 kBtu/sf-yr for health care in the CBECS report.

This result also means that the 20 ATBs located in North and Central America operate about 2% more efficiently, which may decrease operational costs. According to an SFO report, SFO consumed 323,000 MWh of electricity in 2010 (SFO, 2011). This means that the energy performance benchmark for existing or future ATBs can either save or waste over $472,000 per year, based on California electricity rates. In the case of SFO only, the difference between observed and normalized EUI is about 7.6%, which is equivalent to 1,497,380 MWh and $2,188,616. In the case of large–scale–building types like ATBs, the high accuracy of the EUI indicator is required to realistically define potentially large energy consumption or savings. The number of 198.15 kBtu/sf-yr can be used as the U.S. national average site EUI for energy efficient ATBs rather than the simple mean of 194.86 kBtu/sf-yr.

In conclusion, the energy performance benchmark model for ATBs can be used when aninsufficient amount of observed data is provided or when the energy consumption level of mixed-use buildings is not defined in existing surveys. This methodology can also be used to increase the accuracy of the simple mean of observed EUI_{ATB} used in previous models. Further, this methodology can also provide advantages in that the EUI_{ATB} of existing ATBs can be precisely diagnosed and the energy consumption level of future ATB can be effectively predicted. Another advantage is that this methodology can be used to define precise average energy consumption levels of other building types, which are already surveyed, such as office, school, hospital, religious worship, and other small-scaled building types. In this paper, 90 simulation processes and results were utilized to complement the weakness of some measurements and validate the significance of real factors. For future study, using the normalized EUI baseline a more realistic EUI_{ATB} will be suggested for existing and future projects via the more precise and synthetic building complex simulation model.

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