Building energy performance benchmarking and simulation under tropical climatic conditions

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ABSTRACT

Benchmarking is a management approach to identify best practices, find reasons of success and develop recommendations and implementation for improvement. Method of building energy performance benchmarking is discussed in this paper. A database of office buildings in Singapore was presented and used as example for the data analysis and benchmarking method discussion. Concepts of controllable and uncontrollable factors of buildings energy performance are introduced using mathematic model. Method of normalization and determination of performance indicators are discussed. Based on the established benchmarks, typical buildings are to be identified according to energy performance classes and used to find the reasons of success and examine technically feasible energy conservation measures and saving potentials. Computer simulation is then needed to examine the actual, practical and economic measures of energy and cost savings in buildings and develop recommendations and implementation.

1. INTRODUCTION

Benchmarking is a management approach to identify best practices and reasons to make them successful. It is usually used to establish new, more relevant and efficient standards of performance in various areas. These mainly include finance, business management, manufacturing and services. The key elements for benchmarking include continuous systematic search for and identifying best practices, careful study to find the reasons of success, and develop recommendations and implementation of improvement.

Benchmarking has also been widely utilized in the area of building energy performance assessment. Some of the established benchmarking and related programmes include EPA's ENERGY STAR Building Certification Program in USA, Australian Building Greenhouse Rating Scheme, CalArch (California Building Energy Reference Tool), Hong Kong's EMSD Online Benchmarking of Energy Consumption, APEC Building Energy Benchmarking, Carbon Trust from UK, and more recently the EPLabel programme in Europe.

Energy Sustainability Unit of the School of Design and Environment, National University of Singapore has been working in the area of building energy performance assessment and benchmarking for many years. The studied building types include office building, hotel, industrial factory, schools, hospitals and swimming pools. The paper introduces some of the experiences and knowledge learned from those studies and understanding of benchmarking concept. It also discusses benchmarking methodology based on established database of office buildings in Singapore. For a better understanding of the study's background, a brief introduction of Singapore and the office buildings in Singapore is given as follow.

Singapore is an island located at latitudes 1° 19'N and longitudes 104° 'E. It is approximately 137 km north of the equator. The main features of the climate of Singapore are the relatively stable temperature throughout the year and high humidity and abundant rainfall due to the maritime exposure of the island. It has a diurnal temperature range of 23°C to 34°C. The relative humidity (RH) is usually between 65 and 90 percent.

Office buildings in Singapore are often characterized with high grade office space meeting the needs of international tenants and mixed building use such as office cum retail, staff cafeteria and restaurant which provide most convenience. Full building air conditioning is provided during office hours all year round. The majority of energy source in office buildings is electricity, which is used to operate equipment for the safety, efficiency and comfort of its occupants and users. According to Singapore Power's Annual Report 1999, the electricity consumption of office buildings is approximately 1171.3 GWh/year, which is responsible for 11.7% of the overall non-manufacturing sector's consumption, and 4.3% of the national total consumption. Therefore, office may be considered as major energy user among the various building types in Singapore.

2. THE CONTROLLABLE AND UNCONTROLLABLE FACTORS OF BUILDING ENERGY PERFOMRANCE

Benchmarking has been discussed by many authors, primarily in the form of management guidebooks (Wöber, 2002). Figure 1 shows a model of measuring business performance introduced by Anderson (Anderson et al, 1997). The model illustrates that the success of any business firm is a result of the interaction of two major sets of factors. The first factors influence the performance of a business from inside the firm. Those factors that are controlled or determined by managers are named controllable inputs to the model, which are also referred as the decision variables or discretionary variables. In reality, however, there may be factors that are beyond the control of people or a firm's management. These are uncontrollable factors.

The similar concept can be used for energy benchmarking of buildings. In this particular scenario, the controllable factors can be building's design features, operation and maintenance manners, decision on types of systems and equipment, as well as environmental settings and establishing energy management policies; while uncontrollable factors could include weather conditions, geographical locations, floor areas, multiple functions of buildings, business operating hours, building age, occupancy rate, number of people inside the building, etc. In this case, the purposes of identifying these two types of factors are: firstly normalizing building energy consumption by uncontrollable variables to achieve fair benchmarking. Examples include weather normalization, using energy consumption per unit floor area as indicator, energy consumption normalized by operating hours and removing special consumption and areas such as data centres and car parks; and secondly seeking and evaluating energy conservation and cost saving measures of identified best practices with focus on the controllable factors. These include types of chillers, lighting devices, sun shadings, manners of equipment operation and maintenance, and so on. Those measures are significant for the development of recommendation and implementation of building energy efficient design and retrofitting.

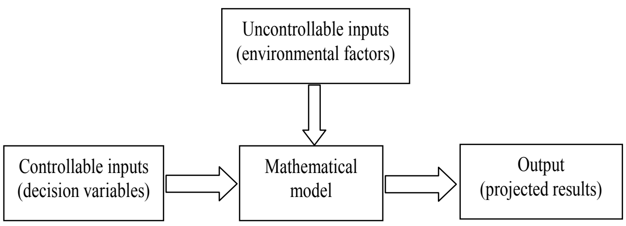

Figure 1: Process of transforming inputs into outputs (Anderson et al., 1997).

In summary, understanding the concepts of controllable and uncontrollable factors and identify them are crucial for building energy performance investigation and benchmarking. At the current stage, uncontrollable factors are the centre of data collection. Detailed information of controllable factors is investigated when best-practice buildings are identified based on the benchmarking results.

3. DATA COLLECTION OF OFFICE BUILDING ENERGY USE AND CHARACTERISTICS IN SINGAPORE

To date, a total of 120 office buildings have been investigated in Singapore, which accounts for approximately 20 percent of the whole population of office buildings in Singapore (REALIS, 2006). Data collections were continuously conducted from 1998 to 2006. Surveys were mostly conducted by questionnaires followed by phone and personal interview, meeting and site visit in buildings. Questions mainly focused on three aspects: 1) building background, for example building age, ownership, building functions, type of HVAC system, environmental settings, age of systems, energy saving design and measures, type of building control system and operating hours of systems, situation of last major retrofitting, etc; 2) space distribution in building, including areas of various function spaces in building, percentage of the areas occupied, operating hours of each function space, number of occupants and number of computers; 3) utility monthly energy consumption data of each fuel type for the same 12 months. This may include the consumptions of landlord, tenants and total building. Information of power demands and energy cost were also required.

After the comprehensive processes of data verification, data screening, normality test, and removing outliers, the final sample frame was determined. As the result, a total of 95 buildings were chosen from the 120 data sets collected and used for further analysis. The sample is found to be representative of the entire commercial office building stock in Singapore, as it covers a wide spectrum of each building parameter. Table 1 gives a summary of the statistics of main parameters.

4. DATA ANALYSIS AND DETERMINATION OF BUILDING ENERGY PERFORMANCE INDICATORS FOR BENCHMARKING

4.1 Normalization of building energy consumption and floor area

Annual total building energy consumption is obtained from the monthly utility data collected.

Calculations of cooling degree hours show that in Singapore the variation of weather from year to year is minor- less than 5% (Meteorological Services Division, 2001). Also since Singapore is definitely located within one climatic zone, it was decided that no weather normalization or correction is needed for buildings consumptions.

The following steps are undertaken to normalize the energy consumptions. Firstly, remove the energy consumptions of car park and data centre area from total consumption. This is because car parks normally occupy large area in office buildings, but have relatively low energy consumptions, as compared to office space, which usually are only used for lighting and mechanical ventilation (Yeo, 2003). On the other hand, data centres are often small but have high energy consumptions of IT equipment, air

Table 1: Basic statistics of main parameters.

Descriptive Statistics

	N	Range	Minimum	Maximum	Mean	Std. Deviation
Building Age	95	21	1	22	11.82	6.055
Public Building(0), Private Building (1)	95	1	0	1	.61	.490
Office(0), Office cum Retail(1)	95	1	0	1	.23	.424
Air Conditioned Area (m2)	95	92811	2006	94817	27163.91	23155.394
Gross Lettable Area (m2)	95	76504	2006	78510	23736.81	19524.025
Gross Floor Area (m2)	95	127994	2006	130000	34174.13	29484.582
Floor Occupy Rate (%)	95	40	60	100	92.93	8.702
Weekly Operating Hours	95	30	44	74	56.33	6.764
Number of People	95	4954	46	5000	1166.86	1045.635
People Density (Peoples/100m2)	95	10	1	10	3.74	1.885
Total Building Energy Consumption (kWh/ year)	95	24539061	328052	24867113	7044613	6087918.605
Valid N (listwise)	95					

* Among the 95 buildings, 37 of them are from public sector and the remaining 58 are from private sector; 73 are office buildings and 22 are office cum retail area which is found to be always less than 10% of the gross floor areas. All of office buildings were upgraded according to the OTTV regulation published in 1979, as such ages of buildings built before 1979 were calculated based on the year 1979.

Table 2: Model summary of stepwise multiple linear regression of TBEC (kWh/year).

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.940[a]	.883	.882	2093205.04
2	.944[b]	.891	.889	2028317.95

a. Predictors: (Constant), GFA
b. Predictors: (Constant), GFA, BU
c. Dependent Variable: TBEC3 original data

* BU is dummy variable, "0" for office, "1" for office cum retail.

Table 3: Coefficients of stepwise multiple linear regression of TBEC (kWh/year).

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	7315970	215002.3		34.027	.000
	GFA	6107263	230481.3	.940	26.498	.000
2	(Constant)	7330474	208409.1		35.173	.000
	GFA	6038552	224831.9	.929	26.858	.000
	BU	569769.4	214657.2	.092	2.654	.009

a. Dependent Variable: TBEC3 original data

conditioning and UPS lost (Sun et al, 2006). Both of the areas can vary significantly from building to building.

Secondly, total building energy consumption was normalized by the building operating hours.

Normalised TBEC = TBEC *(55/OH) (1)

where:
- TBEC: Total building energy consumption
- OH: Operating hours
- 55: Typical weekly operating hours of office buildings in Singapore.

According to the definition given by Urban Redevelopment Authority of Singapore, office building gross floor area is exclusive of car park areas. For the further analysis, unoccupied gross lettable floor area was removed from gross floor area.

Normalised GFA = GFA – GLA*(1- OCR) (2)

where:
- GFA: Gross floor area
- GLA: Gross lettable area
- OCR: Percentage of occupied gross lettable area.

4.2 Regressions to find determinant factors of total building energy consumption

Least square simple linear regressions and stepwise least-squares multivariate linear regression were performed to find the best primary explanatory factors of normalised building energy consumption, using normalized total building energy consumption as dependent variable, and all the other parameters in Table 1 as independent variables, except weekly operating hours and floor occupancy rate, which are already used for normalization of energy consumption. All the independent variables were central standardized before regression. The result is shown in Table 2 and Table 3, and the plot of regression studentized deleted residual against regression standardized predicted value is shown in Figure 2.

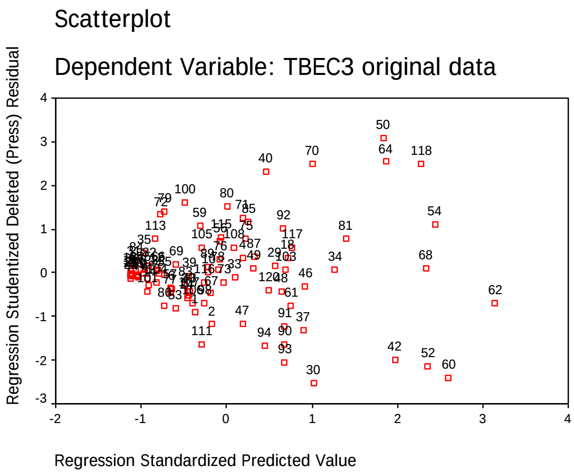

Figure 2: Residual plot of stepwise multiple linear regression (on top of each red square representing one building is the building's ID number).

It shows that GFA alone is sufficient to explain more than 88% of the variability in energy consumption. Hence, it suffices to use GFA as the primary determinant normalization factor. Building function type (BU) can enhance the adjusted R square and reduce standard error with very minor degrees.

Nevertheless, this may call for the need of examining buildings in separated groups, namely office and office cum retail. The results show that GFA is still the primary determinant factor for each sub group. For group A (i.e. office), R square increased by 1.8% than the mixed model. While for group B (i.e. office cum retail), R square decreased 4.9% and increased the variance (8.5%) on prediction. This reflects the impact of small sample size of office cum retail building (22 cases), and probably the more complex building activity inside these buildings than that of office building. For the benchmarking, it may be ideal to separate the buildings into two groups. However small sample sizes becomes the major constraint for group B. Plus, the line between office and office cum retail is not clear enough in data collection, prediction for new buildings could give unexpected result. Therefore, it is decided to keep the building in one group for the further analysis.

The residual plot shows interesting finding. The fan-shaped figure suggests that as X increases, the standard deviation of Y also increases. This can be due to the condition of normal distribution assumption of the regression model, while TBEC and GFA present highly right-skewed distribution or lognormal distribution in the first place, see Figure 3 and 4.

It can be interesting to find out whether there are other possible explanatory factors of build-

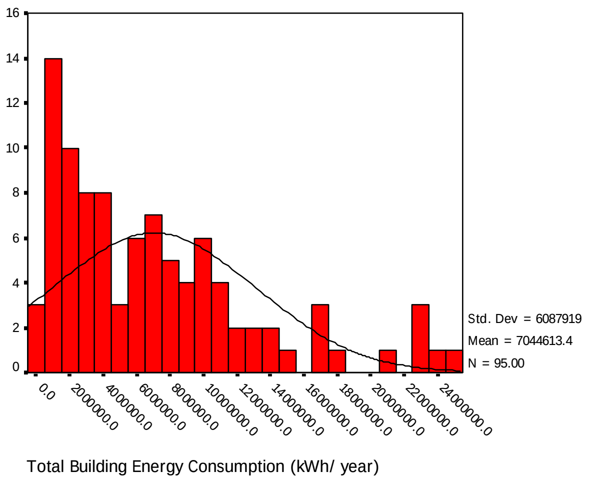

Figure 3: Distribution of total building energy consumption (kWh/year).

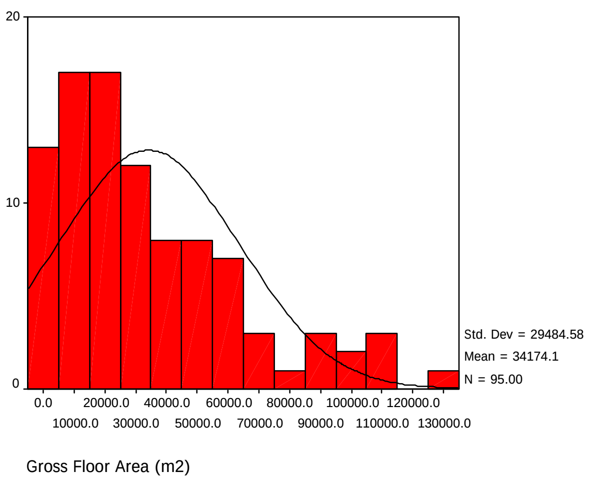

Figure 4: Distribution of gross floor area (m^2).

Table 4: Model summary of stepwise multiple linear regression of EUI ($kWh/m2.year^{-1}$).

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.288[a]	.083	.073	66.969
2	.357[b]	.128	.109	65.672

a. Predictors: (Constant), People Density

b. Predictors: (Constant), People Density, BU

c. Dependent Variable: Energy Use Density (kWh/m2/year)

ing energy consumption after normalized by gross floor area. Therefore, least square simple linear regressions and stepwise least-squares multivariate linear regression were performed following. The dependent variable used was the ratio of total building energy consumption to gross lettable area, further discussion of the ratio is given in the next section. The results show that three parameters have not shown any significant statistical impacts. These include building age, whether building from public or private sector, design efficiency of building (i.e. the ratio of gross lettable area to gross floor area). The respective R squares from simple linear regressions are 0.3%, 0.2% and 0.9%. However, the stepwise multiple linear regression shows that people density (i.e. number of people per 100 square meters of floor area) and building function type (i.e. office or office cum retail) are the explanatory factors. See Table 4. The t statistics show these two factors are significant; however it also shows that people density alone can only explain 8.3% of the variation and together with building function it only increased to 12.8%. This is consistent with the former finding that office and office cum retail building may have different behavior in terms of energy performance. It is expected that people density has impact on building energy consumption. However, firstly the number of people is correlated with gross floor area and second this value is normally based on estimation, which may cause the accuracy and reliability cannot be guaranteed. However, this shows that it would be interesting to use energy consumption per people or energy consumption per unit floor area per people as alternative indicators. The following section gives discussion on the energy performance indicators used in the study.

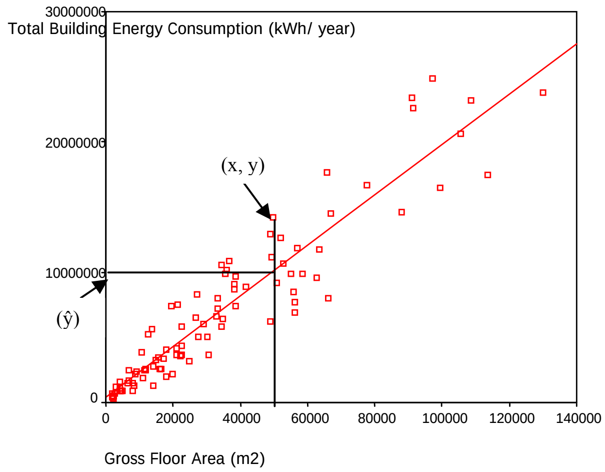

Figure 5: Regression line and points fitted in an analysis for performance indicator- Efficiency Score.

4.3 Energy performance indicators

Three types of performance indicators were proposed in this study. The first type is the ratio of TBEC to GFA, in light of GFA is the only primary determinant factor found in regression analysis. The ratio is called energy use intensity (EUI) with unit of $kWh/m^2.year^{-1}$, which is commonly used by many benchmarking programmes.

The second type is the ratio of TBEC to the number of people inside the building (PEUI), in terms of $kWh/ people.year^{-1}$.

The third type of indicator is called Energy Efficiency Score (EES), which is calculated based on simple linear or multiple regression models (Wöber, 2002). As illustrated in Figure 5, the scale independent efficiency score for each building can be calculated by expressing the difference between observed and predicted energy consumption as a percentage of the predicted energy consumption.

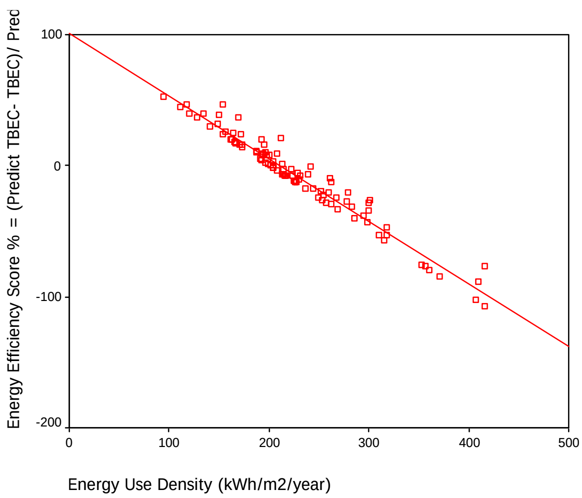

Figure 6: Scatter plot of Energy Efficiency Score against Energy Use Intensity (in the figure EES = (Ŷ- Y) / Ŷ*100).

$$EES = (\hat{Y} - Y) / \hat{Y} \quad (3)$$

where:

- EES: Energy efficiency score
- $\hat{Y}$: Predicted energy consumption
- Y: Observed energy consumption.

Figure 6 shows that EES almost have linear relationship with EUI, which means the two indicators are almost equivalent for the current study. Compared to EUI, EES shows advantages when there are more than one determinant factors.

4.4 Cumulative percentile rating method versus clustering classification method

Figure 7 to Figure 9 shows the results of cumulative percentile distribution by using different performance indicators.

However, it should be careful to make direct comparison by using performance indicators given above or the cumulative percentile scores as indications of building energy performance, especially when two buildings are very similar in terms of the energy performances. For example, it may not be correct to say a building with EUI at180 $kWh/m^2.year^{-1}$ has better performance than a building with EUI at 190 at $kWh/m^2.year^{-1}$. This is because higher energy consumption can be due to some uncontrollable factors such as mixed building function, people behaviors, or a new data centre was built in the middle of the year and etc. Normalization done so far cannot account for the impacts of all the uncontrollable factors. In this case, a classification (e.g. Class A, B, C, D) can give reasonable and reliable results.

Discussions of various classification methods can be found in recent study conducted (Santamouris et al, 2006; Lehmann et al, 2006). In general, it concludes that clustering classification method, which identify natural groupings of objects and classify them according to existing similarities, is better solution than the equal frequency rating method which defines energy classes based on the frequency distribution of buildings and by considering an equal number of buildings for each class, especially when the performance indicators are not normally distributed. Further discussion of performance classification is however beyond the scope of this paper.

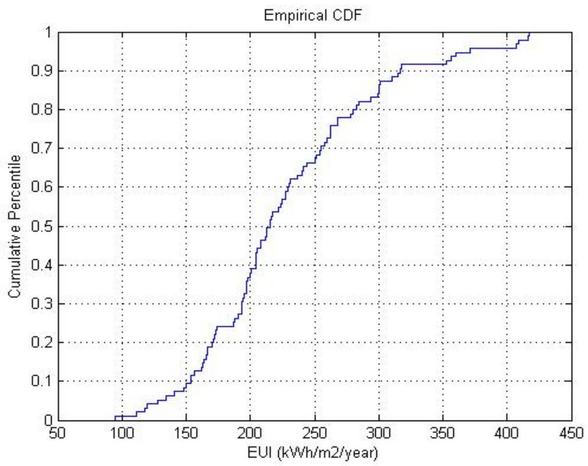

Figure 7: Cumulative percentile distribution of EUI ($kWh/m^2.year^{-1}$).

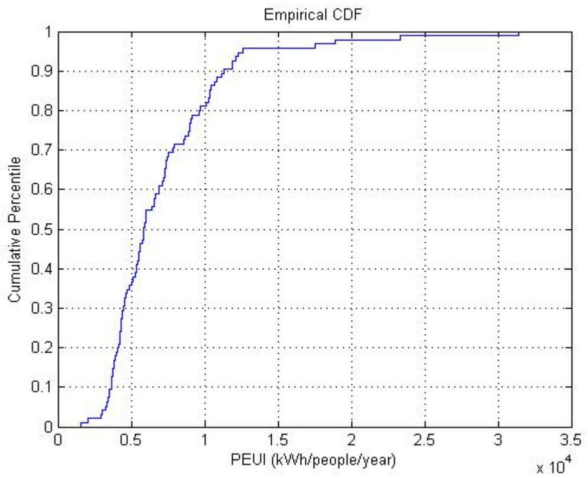

Figure 8: Cumulative percentile distribution of PEUI ($kWh/people.year^{-1}$).

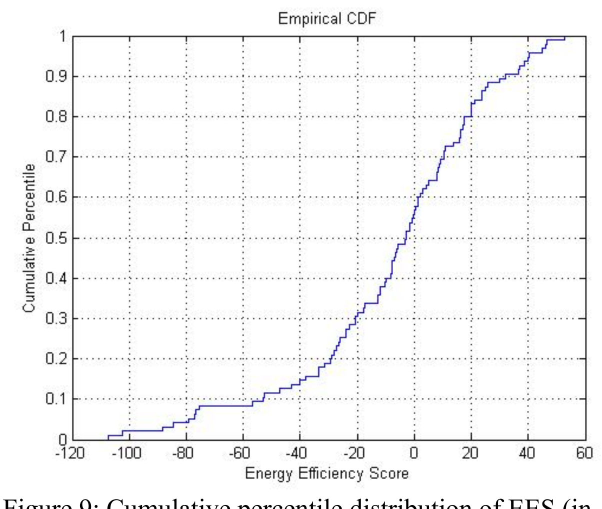

Figure 9: Cumulative percentile distribution of EES (in the figure EES = $(\hat{Y} - Y) / \hat{Y} * 100$).

5. THE USE OF BENCHMARKING RESULTS

The benchmarking results can be used in various areas. Follows are some of the applications have been done, on-going and proposed.

i A volunteering web-based on line building energy performance benchmarking system-Energy Smart Tool was developed by the Energy Sustainability Unit. Users are required to input basic data of building characteristics and energy use, and a preliminary benchmark report will be generated by the tool. Users can know their building energy performances as compared with other similar buildings based on indicator of total building energy consumption per unit of floor area. The tool is available online now at www.esu.com.sg.

In the next phase of development of the tool, it will offer high flexibility for the users, by allowing selection of particular benchmarking partners or sub building groups which the users want to compare with. For example, owner of Building A wants to compare his/her building only with buildings with gross floor area between 5000 m^2 to 8000 m^2, building age less than 10 years, pure office and governmental building. The system will find the comparative benchmarking partners and produce the statistic result in a report according to the user's requirement. The typical outputs include mean, median, maximum/minimum values and standard deviations, as well as other indications of the variability of the sample or population for the entire sub group. This will help define the confidence that one can place on the comparison/ benchmarking. Even though some times the number of buildings in the sub group may not be sufficient to draw a perfect cumulative curve or produce reliable statistics. The benefit of the planned system is that users will learn during the process of choosing comparative benchmarking partners and find most reasonable solutions according to the results and associated information after several times of tries. The users can also choose from multiple energy performance indicators, such as $kWh.year^{-1}$/ gross floor area, $kWh.year^{-1}$/ air conditioned area, $kWh.year^{-1}$/ people, peak kW/ floor area, for a more comprehensive evaluation of overall building performance.

ii Energy Smart Label programme launched in December 2005 by National Environment Agency of Singapore is the first building energy efficiency labelling programme in the region of Southeast Asia. Details of the programme and guideline of application can be found at www.esu.com.sg.

iii The great success of benchmarking is related to its inherent characteristics of being a knowledge-sharing and motivational process. Information such as industrial norm and cumulative percentile based on single performance indicator such as EUI is not sufficient. It is rarely useful without accompanying information. Generally, one would also like to have the indication of the variability of the sample or population in terms of building characteristics parameters such as building age, floor area, building use, design features, operation and maintenance practices and energy use pattern. Information should be provided to building owners for a better understanding of how to interpret benchmarking results and how to use them for managerial purpose. Establishing a national and regional building energy use and performance information centre in this case is the final goal of the benchmarking. The information will be useful for energy researchers, energy policy makers, energy services companies and building owners.

iv Till now, works has been done are focusing at the first step of benchmarking, namely identification of best practices. Much more efforts are needed in the next steps to find out the reasons of successes and give recommendation and implementation plans for buildings.

Firstly, it is important to identify typical buildings based on the classification of building energy performance, that is, to identify which is the typical inefficient building, which is the average performance building and which is the best practice. A recent study has discussed the method of identification of typical buildings using principle component analysis (Lehmann et al, 2006).

Secondly, examine the reasons or factors that cause the different performances and document them. Technical potential, an estimation of overall building energy saving potential based on whole building energy performance benchmarking, can generated at this stage.

Thirdly, based on the information collected computer simulations can be conducted to examine the potential of energy and cost saving. Economic potential, a guideline of energy efficient designs and measures in buildings under tropical climatic conditions, can be generated. Recommendation and implementation can be developed for the energy efficient design of new buildings and retrofitting of existing buildings.

6. CONCLUSIONS

Benchmarking as a management approach is currently widely used for various purposes. It is a continuous systematic process that requires tremendous efforts in data collection, data analysis, modeling, classification, simulation, database development and internet design.

Detailed investigation and understanding of buildings' comparability are important. Office buildings in Singapore are typically characterized by high variations of building functions. The reason of variations can be categorized into three types. They are firstly high people load. For example, more people can be found in buildings with retail areas, restaurants, gyms, governmental and commercial customer services centre than normal office buildings. Secondly, high equipment load. Buildings with data centres, spaces for light industry and lab, banks, media and broadcasting companies which have higher load from IT equipment and computers can have significantly higher energy consumption than other buildings. Thirdly, high services level. For example, many buildings with office space may have gym, club, sauna, swimming pool, spacious atrium and conference hall. In these cases, the higher energy consumptions for buildings are not caused by inefficient systems or poor operations, but by the functions requirements of the buildings. Therefore, it is very important to understand those uncontrollable factors and normalized them. Most of the cases, this is more important than applying advanced data analysis methods for benchmarking practices.

The data collection part of benchmarking is a slow and cautious process that requires mutual trust between building owners and investigators. Formalization of benchmarking partnership at the early stage of conducting data collection is the key for continuous and reliable benchmarking.

Lastly, the discussion given in this paper with respect to data mining and benchmarking method can be applied to other types of benchmarking practices.

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