An approach to develop a green building technology database for residential buildings

To cite this article: Jialei Shen and Jianshun Zhang 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **609** 042063

IOP Conf. Series: Materials Science and Engineering **609** (2019) 042063 doi:10.1088/1757-899X/609/4/042063

An approach to develop a green building technology database for residential buildings

Jialei Shen[1] and Jianshun Zhang[1,2,*]

[1] Department of Mechanical and Aerospace Engineering, Syracuse University, 263 Link Hall, Syracuse, NY 13244, USA
[2] School of Architecture and Urban Planning, Nanjing University, 22 Hankou Road, Nanjing, Jiangsu Province, 210093, China
[*] jszhang@syr.edu

Abstract. Buildings consume approximately 39% of the total energy used in US, of which 53% is consumed by residential buildings. Besides, indoor air quality (IAQ) have significant impacts on occupant health since people spend on average around 90% of their time indoors. Nowadays, a great number of green building technologies (GBTs) have been developed and implemented in buildings for reducing energy consumption and improving IAQ. This paper proposes an approach to develop a green building technology database for residential buildings including their the technology's feature and performance for energy saving and IAQ improvement under different building configuration and climate conditions. The GBTs are collected from case study buildings. For each study case, the GBTs are classified by the Virtual Design Studio (VDS) building assessment method. A local reference building is first defined for the region where the case building is constructed. Both forward-step evaluation of a proposed GBT to a reference building and backward-step tracking of the contribution of the technology to the case building are conducted. A scalability analysis is also conducted to understand the practical application of the performance parameters to other cases with different building design. EnergyPlus and CHAMPS-Multizone are used to analyse the energy and IAQ performance for each technology. The approach is verified by a case study of two single-family houses in US.

1. Introduction

Building energy consumption contributes approximately 39% of the total energy used in US, of which 53% consumed by residential buildings and 47% by commercial buildings [1]. Large energy saving potential exists for residential buildings. Besides, indoor air quality (IAQ) can have significant impacts on occupant health as people spend average around 90% of their time indoors [2]. Human exposure to indoor pollutants like particulate matters (PM), ozone and VOCs, has been proved to be associated with the increases in respiratory-related morbidity, cardiovascular morbidity and premature mortality as well as sick building syndrome and huge loss in productivity [3–7].

Nowadays, a great number of green building technologies (GBTs) like super insulation, enclosure air-tightening, energy recovery, green roof, ground source heat pump, solar panel, demand-based ventilation has been developed and implemented in buildings for reducing energy consumption and improving IAQ. Several performance assessment systems have been developed by different countries/institutions to support the design of high-performance buildings, including LEED, ASHRAE 189.1, BERRAM, WELL, DGNB and WBDG. While these assessment systems provide criteria and pathways to achieve a certain level of performance, they do not provide guidance on how each GBT would improve or contribute to the overall performance directly. A systematic method for evaluating for the performance potential of different GBTs for energy saving and IAQ improvement is needed. Such a method can then be applied to establish a green building technology database by studying adequate green building cases, which can work as a guideline for the green design of new buildings and green retrofit of existing buildings, and further used in modular-based green building design strategy.

This paper proposes an approach to develop a GBT database for residential buildings based on the systematic analysis of green building case studies. For each study case, the GBTs are classified by the Virtual Design Studio (VDS) building assessment method [8,9]. Then, both forward step evaluation of a proposed GBT to a reference building and backward track of the contribution of the technology to the case building are conducted. EnergyPlus and CHAMPS-Multizone are used to analyse the performance for energy consumption and IAQ, respectively. The approach is verified by a case study of two single-family houses in US.

2. Methodology

2.1. Local reference building

GBTs may have quite different performance in different locations, e.g. the shading system used in cold region may not be as efficient as the one used in hot region. The local climate condition and local design strategy may have significant impacts on building performance. Therefore, the performance of each GBT on the studied building will be evaluated by comparing to a local reference building. A local reference building is defined as a building with the same design as the studied building but with the GBTs being replaced by the typical technologies/features commonly used in the local practice per local building code requirement.

The local reference building should be defined in accordance with the typical local design strategy as well as the local criteria in each region and climate zone. Different regions usually have different design strategies and criteria for each type of building. For single-family houses in US, the National Renewable Energy Laboratory (NREL) has developed the benchmark for each climate zone (Building America B10 Benchmark), which is generally consistent with the 2009 International Energy Conservation Code. ASHRAE 90.2 and 62.2 defined the design criteria like envelope construction and ventilation requirement for single-family house in each climate zone, which can be used to define the local reference house as discussed by Liu et al. [10].

2.2. Green building technology collection and classification

GBTs in this study are collected from the existing green buildings. In this study, GBTs are defined as the building technologies and features which can improve the building performance compared to the local reference building. GBTs are collected and classified using the building performance analysis methodology defined in our previous work of the Virtual Design Studio (VDS) assessment method [8,9], which focuses on 10 design factors (Table 1), i.e. site and climate (SC), form and massing (FM), internal configuration (IC), external enclosure (EE), environment system (ENV), energy system (ENG), water system (WS), material and embodied energy (ME), lighting and daylighting (LD), as well as system interdependence (SI). Each technology can be related to more than one design factor.

Table 1. GBTs classification criteria.

Design factor	*Abbr.*	*Description*
Site & Climate	SC	Technologies depended on local site and climate, e.g. ground source heat pump and natural ventilation
Form & Massing	FM	Technologies related to building form and massing, e.g. Trombe wall and solar chimney
Internal Configuration	IC	Technologies related to internal configuration, e.g. layout of the space that minimizes the interzonal cross contamination or conflicting heating and cooling adjacency
External Enclosure	EE	Technologies related to building enclosure, e.g. double-skin façade system, automatically adjusted blinds for shading system
Environmental System	ENV	Technologies related to environmental system which can improve the indoor environment quality, e.g. displacement ventilation combined with radiant cooling, personal heating, cooling and air cleaning system

Energy System	ENG	Technologies related to energy harvesting, storage and distribution that can improve the building energy performance, e.g. PV panel
Water System	WS	Technologies related to water system, e.g. rain water recovery
Lighting & Daylighting	LD	Technologies related to lighting system which can reduce lighting energy consumption, e.g. daylighting system
Material & Embodied Energy	ME	High-performance material used in the building, e.g. high-insulation material and mass material, recycled materials
System Interdependence	SI	Technologies that cut across at least two of the above categories such as PV integrated façade system for harvesting both electricity and thermal energy

2.3. Green performance assessment approach

A performance analysis approach is developed to assess the physical performance of the collected GBTs, i.e. energy consumption and indoor air quality (IAQ). As shown in Figure 1, the forward-step evaluation is applied to understand the potential of an individual technology for performance improvement over the reference house, and the backward-step tracking analysis is to assess the contribution of an individual technology to the performance of the case building in which all identified GBTs are used. In addition, a scalability analysis is conducted to get the practical application of the individual performance potential of each technology to other cases with different building design from the reference building.

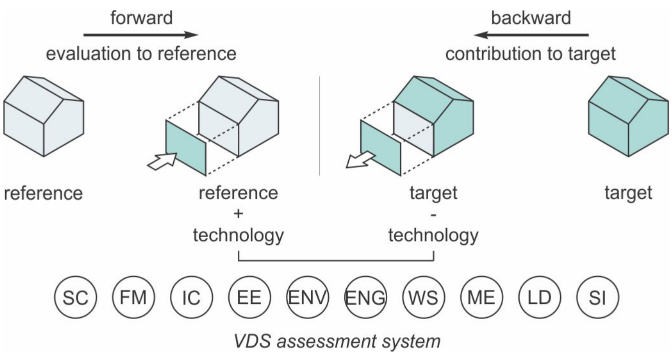

Figure 1. Schematic of the forward-step evaluation and backward-step tracking analysis.

A forward-step evaluation of an individual GBT relative to a reference building would be conducted first to obtain the technology's performance improvement potential ($P_{p,i}$) over the reference performance effect. In this study, P_i indicates the potential of performance improvement using a specific technology i in the reference building, which can be calculated by

$$P_{p,i} = \frac{E_{ref} - E_{ref+i}}{E_{ref}} = \frac{E_i}{E_{ref}} \tag{1}$$

where E_{ref} is the performance effect (energy consumption or IAQ performance) of the local reference building, E_{ref+i} is the effect of a local reference building with the studied technology i, E_i (= E_{ref} - E_{ref+i}) indicates the individual effect potential of the studied technology i and $P_{p,i}$ is the performance improvement potential of the individual technology over the reference building. If $P_{p,i} > 0$, it means that the studied technology i can improve the building performance, while $P_{p,i} < 0$ means that the technology would even deteriorate the performance.

When combining different technologies together in a building, the performance contribution of each technology may differ from the performance improvement potential over the reference building. Therefore, a backward-step tracking analysis is needed to evaluate the of the contribution of the individual technology to a target case building in which all the technologies are applied. This analysis would help understand the performance contribution of the studied technology when combined with other technologies. The performance contribution (α_i) of the studied technology can be calculated by

IOP Conf. Series: Materials Science and Engineering **609** (2019) 042063 doi:10.1088/1757-899X/609/4/042063

$$P_{c,i} = \frac{E_{ref+\Sigma-i} - E_{ref+\Sigma}}{E_{ref+\Sigma}} = \frac{E_i{}'}{E_{ref+\Sigma}} \tag{2}$$

where $P_{c,i}$ is the performance contribution of technology i over the target building with combined technologies, $E_{ref+\Sigma}$ is the effect of the target building with all the technologies applied, $E_{ref+\Sigma-i}$ is the effect of the target building with all the technologies except the studied technology i and E_i' is the individual effect of the technology i.

The ratio between $P_{c,i}$ and $P_{p,i}$ represents the how much the potential of technology i is amplified (if larger than 1) or discounted (if less than 1) due to the synergistic effects with the other technologies applied concurrently:

$$S_i = P_{c,i}/P_{p,i} \tag{3}$$

The individual performance potential of the studied technology is obtained from the analysis to a local reference building, which can be calculated by

$$\alpha_i = E_i'/E_i \tag{4}$$

However, when the studied technology is implemented in a target building with different area, geometry and configuration from the reference building, the performance potential may vary as well. A scalability evaluation is therefore conducted to the studied technology. The scaling factor (β_i) can be derived as

$$\beta_i = P_{c,i}'/P_{c,i} \tag{5}$$

where β_i is the scaling factor, P_i' is the performance potential of the studied technology implemented in the target building and P_i is the performance potential of the studied technology. Each GBT should have its own scaling factor. The ovrall scaling factor of a technology can be calculated by multiplying all the scaling factors of the technology. For some technologies, the scaling factor is an internal integrated parameter of the technologies.

The combined performance potential of multiple technologies to a target building then can be obtained by equation (6). It should be mentioned that the performance contribution α_i and scaling factor β_i in this study could be either constant or variable.

$$P = \sum_{i=1}^{n} \alpha_i \cdot \beta_i \cdot P_i \tag{6}$$

2.4. Performance simulation tools

The performance of the studied building technology is obtained by simulation. EnergyPlus is used to analyze the energy performance and CHAMPS-Multizone is used to analyze the IAQ performance. The energy and IAQ performance parameters such as heating energy consumption, cooling energy consumption, lighting consumption, water heating consumption, ventilation consumption, water use, and indoor pollutant level, would be analyzed using the simulation tools. EnergyPlus is a widely used simulation tool to model both energy consumption and water use in buildings, which is released by DOE. CHAMPS-Multizone is a multizone indoor pollutant transport simulation tool developed by BEESL, Syracuse University.

2.5. Case study

A case study is implemented to verify the proposed approach. Two single-family houses in New York City (climate zone: 4A) and Miami (climate zone: 2A) are analyzed. The local reference buildings are defined following the protocols presented by NREL [11], which is a two-story house with pitched roof and unconditioned attic. Three technologies are analyzed on the reference buildings in these two locations using the presented approach, i.e. high-insulation exterior wall, controlled shading system and air-tight wall assembly. The total building area is 334.61 m^2 with 223.07 m^2 conditioned area.

IOP Conf. Series: Materials Science and Engineering **609** (2019) 042063 doi:10.1088/1757-899X/609/4/042063

3. Results and discussion

The annual heating and cooling energy consumptions of the study cases are simulated by EnergyPlus. The annual heating and cooling consumption of the local reference buildings in two cities are shown in Table 2.

Table 2. Heating and cooling energy consumption of the reference buildings.

Study case	*Climate Zone*[1]	*Energy use [kWh/m²]*	*Ref*	*A*[2]	*B*	*C*	*A+B*	*A+C*	*B+C*	*A+B+C*
New York City, NY	4A	Heating	47.9	44.5	47.3	38.5	43.8	35.3	37.9	34.7
		Cooling	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3
Miami, FL	2A	Heating	2.5	2.2	2.5	1.9	2.2	1.6	1.9	1.6
		Cooling	24.3	23.3	24.0	22.4	23.3	21.8	22.4	21.8

[1] Climate zone defined in ASHARE 169.
[2] A: highly insulated wall; B: controlled shading system, i.e. shading will turn on if the solar irradiation on the window is too high; C: air-tight wall assembly.

Then the performance potential P_i and performance contribution α_i of each technology is obtained (Table 3). The scalability evaluation is not conducted in this paper. The performance potential shows that air-tight wall contribute more to the performance improvement compared to the other two technologies, particularly for heating consumption. The performance contribution to combined technologies indicates that these three technologies are basically independent because the contribution coefficients for each technology are very close to 1. But the air-tight wall may not work well when combined with the other technologies for cooling condition in New York City. Another reason for this situation may be the elevated calculation error caused by the very small value of the performance potential for air-tight wall in cooling condition (0.0004). Using the obtained performance potential and contribution coefficients, the combined performance potential estimated by equation (4) is consistent with the performance potential simulated by EnergyPlus since the estimation error is basically within 5%. Therefore, in this paper, the GBT performance assessment approach can perform well to present the performance potential and contribution of different technologies. A GBT database built by this approach would be a good tool to understand the performance potential of different technologies.

Table 3. Performance potential P_i and performance contribution α_i of each technology.

Study case	*GBT*	*Condition*	P_i	α_i[1]			
				A	*B*	*C*	*AB/BC/AC*
New York City	A[2] (High-insulated wall)	Heating	0.069	/	0.98	0.98	0.96
		Cooling	0.011	/	0.98	0.87	0.85
	B (Shading system)	Heating	0.015	0.92	/	1.00	0.92
		Cooling	0.006	0.96	/	0.95	0.91
	C (Air-tight wall)	Heating	0.197	0.99	1.00	/	0.99
		Cooling	0.0004	-2.27	0.30	/	-2.93
Miami	A (High-insulated wall)	Heating	0.083	/	0.96	0.94	0.91
		Cooling	0.036	/	0.99	0.96	0.96
	B (Shading system)	Heating	0.016	0.85	/	0.98	0.85
		Cooling	0.005	0.95	/	0.94	0.90
	C (Air-tight wall)	Heating	0.255	0.98	1.00	/	0.98
		Cooling	0.070	0.98	1.00	/	0.98

[1] The performance contribution here is the contribution of the studied technology to the combination with different technologies.
[2] A: high-insulated wall; B: controlled shading system; C: air-tight wall assembly.

IOP Conf. Series: Materials Science and Engineering **609** (2019) 042063 doi:10.1088/1757-899X/609/4/042063

4. Conclusion

This paper presents an approach to develop a green building technology database. The technologies are collected and classified based on the VDS system. Three factors are proposed to quantify the performance potential, contribution and scalability of the technologies. According to the case study, the approach works well to present the technology performance. Further extension of the approach would include the study of synergistic effects of any two or more GBTs applied in cases where more than 3 GBTs are applied to help identify the most effective combinations of GBTs for a given building design.

References

[1] U.S. Energy Information Administration, January 2019 Monthly Energy Review, Washington, DC, 2019. www.eia.gov/mer.

[2] N.E. KLEPEIS, W.C. NELSON, W.R. OTT, J.P. ROBINSON, A.M. TSANG, P. SWITZER, J. V BEHAR, S.C. HERN, W.H. ENGELMANN, The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants, J. Expo. Sci. Environ. Epidemiol. 11 (2001) 231–252. doi:10.1038/sj.jea.7500165.

[3] J.M. Samet, F. Dominici, F.C. Curriero, I. Coursac, S.L. Zeger, Fine Particulate Air Pollution and Mortality in 20 U.S. Cities, 1987–1994, N. Engl. J. Med. (2000). doi:10.1056/NEJM200012143432401.

[4] D.B. Day, J. Xiang, J. Mo, F. Li, M. Chung, J. Gong, C.J. Weschler, P.A. Ohman-Strickland, J. Sundell, W. Weng, Y. Zhang, J. (Jim) Zhang, Association of Ozone Exposure With Cardiorespiratory Pathophysiologic Mechanisms in Healthy Adults, JAMA Intern. Med. 177 (2017) 1344. doi:10.1001/jamainternmed.2017.2842.

[5] N. Tagiyeva, A. Sheikh, Domestic exposure to volatile organic compounds in relation to asthma and allergy in children and adults, Expert Rev. Clin. Immunol. (2014). doi:10.1586/1744666X.2014.972943.

[6] R.D. Brook, S. Rajagopalan, C.A. Pope, J.R. Brook, A. Bhatnagar, A. V. Diez-Roux, F. Holguin, Y. Hong, R. V. Luepker, M.A. Mittleman, A. Peters, D. Siscovick, S.C. Smith, L. Whitsel, J.D. Kaufman, Particulate matter air pollution and cardiovascular disease: An update to the scientific statement from the american heart association, Circulation. (2010). doi:10.1161/CIR.0b013e3181dbece1.

[7] B. Brunekreef, S.T. Holgate, Air pollution and health, Lancet. (2002). doi:10.1016/S0140-6736(02)11274-8.

[8] P. Michael Pelken, J. Zhang, Y. Chen, D.J. Rice, Z. Meng, S. Semahegn, L. Gu, H. Henderson, W. Feng, F. Ling, "Virtual Design Studio"—Part 1: Interdisciplinary design processes, Build. Simul. 6 (2013) 235–251. doi:10.1007/s12273-013-0110-2.

[9] J. Zhang, P. Michael Pelken, Y. Chen, D.J. Rice, Z. Meng, S. Semahegn, L. Gu, H. Henderson, W. Feng, F. Ling, "Virtual Design Studio"—Part 2: Introduction to overall and software framework, Build. Simul. 6 (2013) 253–268. doi:10.1007/s12273-013-0111-1.

[10] Z. Liu, R. Zhang, T. Stenson, A. Rais, W. Chen, J. Zhang, Definition of a Reference Residential Building Prototype for Evaluating IAQ and Energy Efficiency Strategies, in: Heal. Build. 2017 Asia, 2017.

[11] E. Wilson, C.E. Metzger, S. Horowitz, R. Hendron, 2014 Building America House Simulation Protocols, Natl. Renew. Energy Lab. (2014).