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Benchmarking Hong Kong and China energy codes for residential buildings

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ABSTRACT

Mandatory energy codes to curb energy use of residential buildings have been formally launched in China for more than two decades but little has been publicized in literature. Similar codes are not available for residential buildings in Hong Kong, but most residential buildings in Hong Kong, especially public housing estates, are HK-BEAM certified to demonstrate their compliance with regulatory and basic design requirements. Given HK-BEAM is internationally recognized and there are doubts about the effectiveness of the China codes, how the energy efficiency of the HK-BEAM certified buildings compare with buildings in compliance with the China codes is of interest to most building designers and policy makers. This paper describes how the energy efficiency of a case study building in compliance with the China codes compare with the one in compliance with HK-BEAM. The energy simulation by HTB2 and BECRES reveal that the case study building in compliance with the China codes is 51.1% better in energy use. In the study, the relative impact of each compliance criterion on energy use and cooling load has been quantified by sensitivity analysis. The sensitivity values indicate that energy use is most sensitive to air-conditioning operation hours, indoor design temperature, coefficient of performance (COP) of the room air-conditioners (RAC) units, and the envelop characteristics. The results of this study indicate that a HK-BEAM certified building cannot satisfy the China codes requirements. This provides good reference to the policy makers, the building owners, and to the China and Hong Kong Governments when considering reciprocal recognition of building energy codes.

1. Introduction

There are growing concerns about the energy consumption and its implications to the world environment. Buildings are the dominant energy consumers in modern cities but their consumption can be largely cut back through improving efficiency, which is an effective means to lessen greenhouse gas emissions and slow down depletion of non-renewable energy resources. However, the potential energy cost saving alone is hardly a sufficient incentive to invest into improvement measures, unless the cost of using energy soars. The use of mandatory codes for controlling energy use in buildings emerged in the mid-70s [1]. It is by far the most widely adopted means for enhancing building energy efficiency, and has been adopted in over 30 countries and regions including some developing economies like China, Taiwan and Argentina [2–4].

In China, energy efficiency efforts began in the early 1980s; in response to the continuous increase in energy use of the residential sector, in particular air-conditioning and heating [5]. With the support of the Ministry of Construction (MOC), an energy efficiency code for residential buildings in the cold zone of the country was first introduced in 1986. The cold zone was chosen because more than half of the country's residential area is located in the northern part where the heating season lasts for 3–6 months [6]. Since 2000, the effort has been extended to cover zones with hot summer and warm winter where energy consumed is primarily electricity for air-conditioning.

Although the energy codes in China have been developed over two decades, there seems to be no published information as to their effectiveness or whether they have been well received by the industry. There are only critiques about the Chinese codes not comparable to similar codes used in developed countries, especially for the requirements on heat transfer coefficients and air-tightness indices of the building envelope [7,8]. However, the comments may not be fair because there are other factors affecting the building energy efficiency that have not been evaluated. Examples would be the efficiency of the equipment; the system characteristics; and the operational needs. Furthermore, as China covers a vast geographical area, and the temperature difference from the south to north is very large, the code standards may have taken into account optimizing the energy consumed for summer cooling and winter heating.

According to the national "Standard of Climatic regionalization for Architecture GB50178-93" [9], China is divided into five climate zones. They are the very cold; cold; hot summer and cold winter;

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hot summer and warm winter; and moderate zones. Hong Kong is geographically located at the hot summer and warm winter zone of China and is often considered as a developed city. Regulatory and voluntary efforts started in 1994 to enhance the energy efficiency of the building sector in Hong Kong. Regulatory efforts are mostly focused on the commercial sector, whilst voluntary efforts are on both sectors. The implementation experience of a policy mix involving both efforts proved successful and has received world-wide recognition [10]. Building on this success, a question is raised whether residential buildings that are in compliance with the Hong Kong codes are equally good as buildings designed in accordance with the China codes. Given Hong Kong's sovereignty has been returned to China and there are concern about the effectiveness of the China codes, it is recognized the need to benchmark the China codes against the Hong Kong codes.

To benchmark the energy efficiency standard of the China codes against the Hong Kong codes, focus is on the energy use for air-conditioning. A representative residential building will be chosen as the case study building. The case study building will comprise of the typical characteristics of the modern high-rise residential buildings in Hong Kong. It will consist of a large number of flats, each of which includes one to several bedroom(s), a combined living and dinning room or, for bigger flats, separate living and dinning rooms, and other rooms such as kitchen and bathroom(s). Bedroom, living room (or combined living and dining room) and dining room are typically provided with independent window or split-type air-conditioners [11]. In this study, the actual layout of the case study building will be used whilst the façade and the fenestration details will be re-defined according to the China and Hong Kong codes.

Despite that there is a lot of good software available for evaluating the energy use for air-conditioning of the case study building, e.g. DOE-2 by LBNL [12], SMASH by Institute for Building Environment and Energy Conservation in Japan [13], and DeST by Tsinghua University in China [14], HTB2 and BECRES [15,16], which will be used in this study. They were chosen because HTB2 and BECRES have come into widespread use in Hong Kong since the introduction of mandatory codes and voluntary schemes in 1996 [17]. Its use is as an energy consumption compliance tool. Previous evaluations indicate that both HTB2 and DOE-2 are in compliance with ASHRAE Standard 140 and can be considered acceptable to each other [18]. Based upon the simulation results, sensitivity analysis will be conducted to evaluate the relative impact on energy use for various compliance criteria in the two codes.

2. China context

China is the country with the largest population in the world. It has had double-digit rates of economic growth in the past two decades. This growth and a desire for improved living standards spurred rapid construction in the past 20 years. This rapid construction has tremendous impact to the energy consumption and the environmental conditions in China; in particular the energy use intensity (consumption per square meter) for heating and air-conditioning for residential buildings. Currently, China's building sector accounts for 23% of total energy use and will possibly increase to one-third by 2010, of which the domestic sector accounts for 10% of the total energy use [19]. In response to the continuous growth of energy use in the residential sector, the government decided to introduce legislative control over the residential building envelope design in the 1980s. The first building energy code "Energy Conservation Standard for New Heating in Residential Buildings JGJ26-86" was introduced in 1986. The revised version, JGJ26-95, with an increased energy-saving goal, was issued in December 1995 [20]. Since then, many other codes have been introduced to different climate zones in China. Examples include the codes of practice for energy efficiency of the heated and air-conditioned residential buildings (JGJ134-2001) [21]; the renovated residential buildings (JGJ129-2000) [22]; and the inspection of heated residential buildings (JGJ132-2001) [23]. They were issued in 2001 for the cold and very cold zones. In July 2003 a design standard for energy efficiency of residential buildings in hot summer and warm winter zone (JGJ75-2003) [24] was also issued.

Recently, a new design standard for energy efficiency in residential buildings covering all climate zones in China has been introduced and consultation is underway. It is modeled from the former industrial standards to cover the whole of China as a national standard. This standard, together with the one previously issued "Design Standard for energy efficiency of public buildings GB50189-2005" [25] constitute the China's building energy codes (hereunder abbreviated as China codes). The codes set standards for design and selection of envelope components, and the heating and air-conditioning systems. The lighting system design is cross-referenced to another standard titled "Lighting design in buildings (GB50034-2004)" [26]. This standard is not mandatory for residential buildings because lighting system design is most often determined by the users.

The China codes (except those voluntary standards) are mandatory and are enforced by the MOC, irrespective of if they are new buildings or existing buildings. Considering the balance between energy efficiency and cost effectiveness, 15% deviation from the codes' requirements is allowed. This is to account for the variations in climate conditions, energy supply and demand, economic developments, environmental conditions, etc., across regions and provinces. On the basis of the national standards, regional and/or local authorities are encouraged to set up local and more specific standards. Major cities like Beijing, Shanghai, Chongqing, Shanxi, Huibei, etc., have already established their local standards [27]. To enhance the implementation of the national standards, the Chinese government requires administrations at provincial-level. Provincial regulations and codes therefore play an important role in implementing the national standards.

The compliance criteria of the codes for new buildings emphasize the avoidance of excessive heating/cooling energy to counter poor envelope performance and low efficiency heating/cooling methods. There are two compliance approaches that focus on the envelop performance. One is prescriptive approach, stipulating the maximum allowable heat transfer coefficients for various building envelope components at the prescribed shape factors (area of a particular envelope component to floor area). Envelope heat transfer coefficients, shading coefficients and window-to-wall area ratios based on orientations are stipulated for different climate zones. If the design of the residential building cannot satisfy the prescriptive requirements, the performance-based approach is used to assess the building efficiency. This approach stipulates the maximum allowable heating/cooling energy consumption of a building in comparison to a baseline case. The baseline case differs for different climate zones in China which is classified by very cold and cold zone, hot summer and cold winter zone and hot summer and warm winter zone. The consumption of a baseline residential building in a very cold and cold zone refers to the "energy budget" estimated by the numbers of heating and cooling degree-days. However, in the other two zones the energy budget is determined by simulating the energy use of the designed building incorporating a range of stipulated requirements. The building will then represent the baseline case whose energy performance barely meets the standard's prescriptive requirements. The use of two approaches aligns with most international codes and standards [28,29], and can be applied to all types of residential structures, including single-family residences, low-rise buildings, and high-rise buildings.

As for the heating and air-conditioning systems of residential buildings, the codes stipulate mandatory requirements for energy efficiency of central heating system installed at very cold and cold zone. But for domestic air-conditioning system in the other two zones, only voluntary requirements are introduced, except for buildings using unitary chiller of nominal cooling capacity exceeding 7.1 kW. The voluntary requirement refers to the minimum coefficient of performance (COP) of room air-conditioners (RAC units) in accordance to "Standard of the minimum allowable values of the energy efficiency and energy efficiency grades for room air-conditioners GB12021.3-2004" [30]. For buildings installed with large capacity chillers, the codes stipulate that relevant items in Standard GB50189-2005 need to be strictly followed.

Judging from the compliance approaches and criteria adopted in the China codes, it can be seen that they were developed based on the international standards like ASHRAE [31].

3. Hong Kong context

In Hong Kong, the Buildings Department scrutinizes and approves building plans through enforcement of the Buildings Ordinance and the related Regulations, which are published in the form of codes of practice and practice notes. The codes of practice are mostly voluntary in nature whilst the practice notes are issued by the authorities and are meant to be mandatory. Legislative control of the codes of practice and the practice notes are introduced in the relevant Building Regulations. However, they are often set to ensure buildings satisfy the minimum safety and health requirements, and little has been stipulated to promote energy efficiency of buildings.

In 1994, the Hong Kong Government took the initiative to establish the Energy Efficiency Office (EEO) and a well-recognized initiative of the EEO is the publication of five codes of practice on energy efficiency of commercial buildings. Focus is given to commercial buildings because they account for 61% of the total primary energy requirement in Hong Kong, whilst the residential sector is only 24%. The first building energy code is on overall thermal transfer value (OTTV) of buildings [32], published in 1995 and enforced by the Buildings Department. In 1998, the EEO issued three other codes of practice covering the energy efficiency of lighting, air-conditioning and electrical installations in buildings, respectively [33–35]. The code on the energy efficiency of lifts and escalators was launched in 2000 [36]. The codes are collectively referred to as the building energy codes in Hong Kong, which adopted a prescriptive approach and set out minimum requirements for achieving energy-efficient design of building envelope, AC installation, lighting and electrical installations in buildings. With the exception of the OTTV code, the published codes originally intended for mandatory implementation are currently being implemented on a voluntary basis under the Hong Kong Energy Efficiency Registration Scheme (EERS) for Buildings launched in 1998. According to the statistics of the EEO up to June 2007, 1896 registration certificates were issued to 762 building venues involving 2110 installations [37].

As for the residential buildings, the EEO has been operating a voluntary Energy Efficiency Labeling Scheme (EELS) since 1995. The scheme covers household appliances including room air-conditioning (RAC) units, refrigerators, washing machines, electric clothes dryers, compact fluorescent lamps, electric storage water heaters, electric rice-cookers, dehumidifiers, television sets and electronic ballasts. In March 2005, the HKSAR government has put forward a consultative paper to solicit views on mandating EELS for specified appliances including refrigerators, RAC units and compact fluorescent lamps [38] to promote energy efficiency of the residential sector. Results of the consultative exercise confirmed that the majority of respondents agreed to the idea of mandatory EELS. It is noted that implementation is subject to final legislative procedures [39].

In 2001, the Government put forward a new scheme in the form of exemption from calculation of floor area or site coverage, as initiatives for the construction of buildings with environmentally friendly features. The scheme applies to both residential and commercial buildings. For proper allocation of incentives, the Government commissioned a consultant to design a comprehensive environmental performance assessment scheme (CEPAS) [40,41]. The scheme is to provide a common yardstick for the measurement of the environmental performance of buildings. However, due to public concern about using government revenue to subsidise the building developers, CEPAS was later changed into a voluntary scheme, intending to use market force to promote green buildings. The scheme was released in March 2007.

Notwithstanding the government initiatives, the Real Estate Developers Association of Hong Kong initiated the development of a voluntary building environmental assessment scheme for Hong Kong in 1994. The resultant scheme, known as the Hong Kong Building Environmental Assessment Method (HK-BEAM), was first launched in December 1996. The first two versions of HK-BEAM are for new and existing office buildings, and cover a wide range of environmental issues related to the impacts of buildings on the environment in the global, local and indoor scales. In 1999, a new version of HK-BEAM (HK-BEAM 1/99) for new residential buildings was issued, which covers similar environmental issues as the first two versions of HK-BEAM [42]. Extensive reviews of the first two versions of HK-BEAM were subsequently made in 1999 and 2004, leading to the publication of the two revised documents in 2004, one for new buildings (4/04) and the other for existing buildings (5/04) [43]. The latest revisions made were to expand the range of building developments that can be assessed; to include additional issues like building quality and sustainability; and to increase the weightings given to building energy efficiency. One of the major changes is the adoption of a new energy performance assessment framework that is based on the energy budget approach [44]. The assessment is made by calculating the annual energy use for the assessed building and comparing it against the energy use of a commensurate baseline building, both of which are to be determined by computer simulation.

HK-BEAM has received very good participation levels since the scheme was launched. At the end of 2004, 96 landmark developments have been successfully assessed, covering 5.1 million m^2, and including 49,000 residential units and 40 Grade A[1] office buildings. At least 10 office buildings have been encouraged to change the existing installations to incorporate energy efficient design. Recently, obtaining HK-BEAM certification has become a standard requirement for buildings developed by the Hong Kong government as well as a few major developers.

Both HK-BEAM and CEPAS are considered voluntary schemes. They are in line for 83% of the issues. In certain cases CEPAS refers directly to the criteria and assessment methods adopted by HK-BEAM [41,43]. In energy assessment, both schemes adopt an energy budget approach, and the baseline levels are set conforming to the relevant regulatory requirements or the basic design requirements. The regulatory requirements include those on health and safety issues [44]. Given HK-BEAM embraces all

[1] Grade A, B and C buildings differ in terms of their quality of facilities provided, with Grade A buildings best equipped and Grade C least equipped [45].

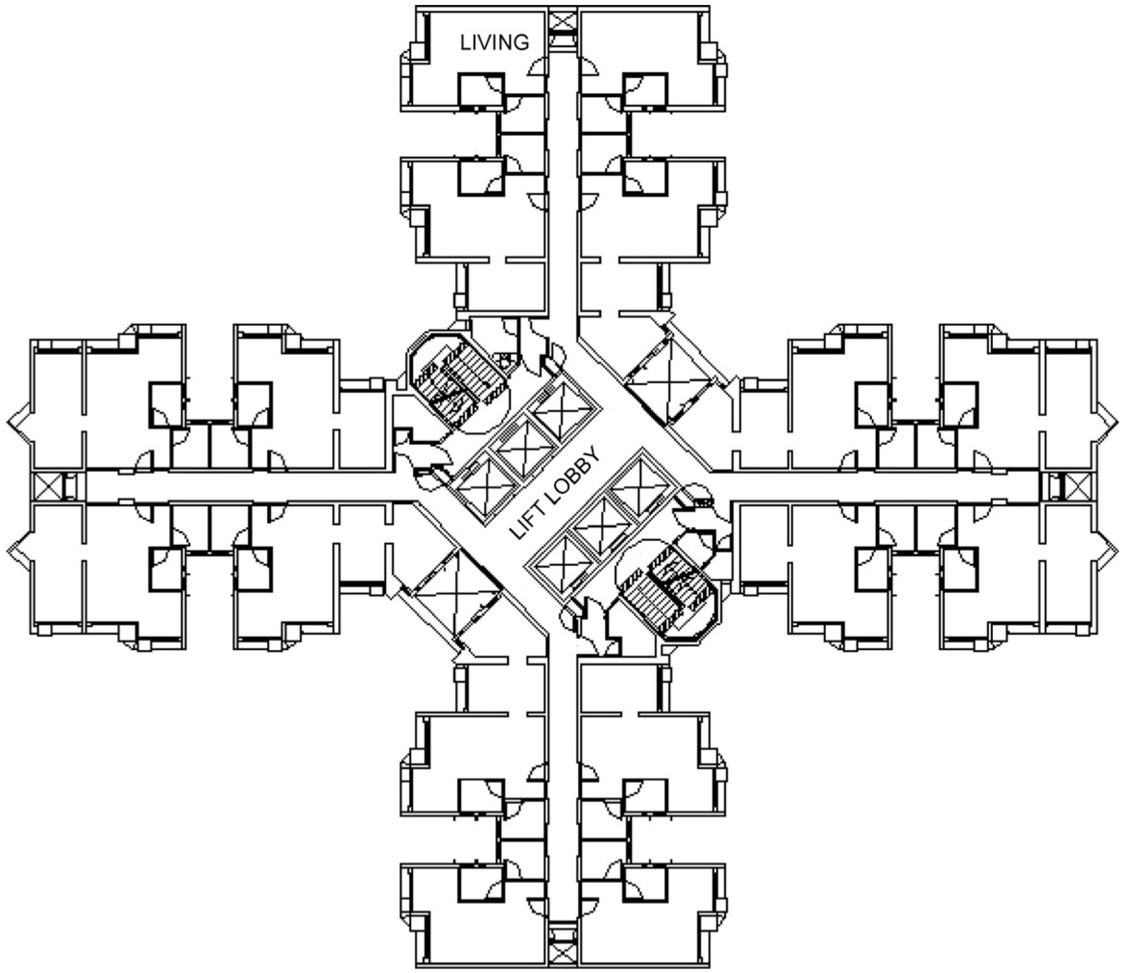

Fig. 1. Floor layout of the case study building.

regulatory, as well as typical design, requirements and little has been stipulated in the mandatory codes for energy efficiency of residential buildings (except the mandatory EELS), it is reasonable to benchmark the China codes (hot summer and warm winter zone) against the energy-related baseline requirements of HK-BEAM.

4. The case study building

For benchmarking the China codes and HK-BEAM, a case study building, which is a 40-storey, 16 flats per storey, harmony type 1[2] public housing block in Hong Kong was chosen as a common basis for evaluation. It was chosen because over 40% of the population in Hong Kong reside in this type of residential block [46] and it comprises all the typical characteristics of modern residential buildings in Hong Kong. So as to cater for the wide variations in operation pattern, internal heat gain intensity, construction details, etc., of different residential units, the case study building was sub-divided into different operating zones. Each zone is treated as an independent space. The living/dining rooms and bedrooms are air-conditioned, whilst the common area, the kitchens and the bathrooms are un-conditioned. Input files were prepared for each space for HTB2 simulation to determine the thermal performance and the cooling load profile. BECRES was used to predict the electricity consumption for air-conditioning of different zones.

Fig. 1 shows the layout of the case study building. Each floor comprises 16 units, facing 4 major orientations, i.e. north, east, south and west. There are four layout types: no bedroom unit, one-bedroom unit (two types) and two-bedroom unit. Each unit is provided with one bathroom, one living room and one kitchen. The physical characteristics of the four layout types are given in Table 1.

5. The baseline criteria

Both the China codes and HK-BEAM adopt the energy budget approach for assessing compliance with the stipulated requirements, which provides flexibilities in making trade-offs among the performances of different envelope assemblies and service systems. In both cases, the energy budget is the predicted annual energy use of the assessed building incorporating a range of baseline criteria.

In the China codes, the criteria that have to be strictly complied with include the indoor design temperature, the *U*-values for the building façade, window-to-wall ratios, the ventilation rate, the coefficient of performance of the air-conditioners, and the shading coefficients of window glass by orientations. Other criteria, including the lighting intensity, the occupancy density and the small power intensities are not mandatory requirements but they are default values for energy budget calculation, which indirectly, govern the maximum allowable energy use of the assessed

[2] Block types are classified by the method of construction and the floor layout. Three most popular types are: the cruciform, the new cruciform, and the Harmony types. They differ by the method of construction and the floor layout.

Table 1
Physical characteristics of the case study building

Area (m^2)	No bedroom flat	One bedroom flat (type 1)	One bedroom flat (type 2)	Two bedroom flat
Bedroom 1	–	7.5	–	7.5
Bedroom 2	–	–	–	8
Bedroom 3	–	–	13	–
Dining and living room	26	26	26	26
Kitchen	5.2	5.2	5.2	5.2
Bathroom	3.2	3.2	3.2	3.2
Total area	34.4	41.9	47.4	49.9
No. of flats per floor	4	4	4	4
Total no. of storeys	40			

building. Similarly for the daily, weekly and yearly operation schedules whereby default values are given in the codes.

Similar criteria are specified in HK-BEAM but some are in different formats. *U*-values for the wall, the roof and the window glass are not explicitly specified in HK-BEAM, but they can be determined from the default construction details, and are compared with the corresponding China codes requirements in Table 2. The default occupation and operation patterns for occupants, lighting and small power are different; likewise for the default air-conditioning operation schedules. HK-BEAM specifies a longer yearly operation schedule, and provides separate schedules for bedrooms and living rooms, whilst the China codes provide separate schedules for weekdays and weekends. Difference in the unit used is also observed in various criteria including small power intensity, ventilation rate, and occupancy. Hence, for the purpose of benchmarking, the criteria stipulated in the China codes and HK-BEAM need to be converted into equivalent parameters.

6. The equivalent parameters

In establishing the equivalent parameters, reference is made to the formulae for design cooling load estimation according to ASHRAE's CLTD/SHGF/CLF method [47]. The annual cooling load (ACL) of a building for a given total air-conditioned hours (HR_{AC}) can be expressed as:

$$\begin{aligned}\mathrm{ACL} = [&(\mathrm{AW}\times\mathrm{UW})\times\overline{T_o} - (\mathrm{AW}\times\mathrm{UW})\times T_a + (\mathrm{AG}\times\mathrm{UG}) \\ &\times\overline{T_o} - (\mathrm{AG}\times\mathrm{UG})\times T_a + (\mathrm{AG}\times\mathrm{SC})\times\overline{\mathrm{SHGF}}\times\overline{\mathrm{CLF}} \\ &+ \rho_a\,\mathrm{Cp_a}\,\mathrm{VR}\times\overline{T_o} - \rho_a\,\mathrm{Cp_a}\,\mathrm{VR}\times T_a + \rho_a h_{fg,0}\,\mathrm{VR}\times\overline{W_o} \\ &- \rho_a h_{fg,0}\,\mathrm{VR}\times W_a + C_1 Q_{LGT} + C_2 Q_{SPW} + C_3 Q_{OCC}] \\ &\times \mathrm{HR_{AC}} \qquad (1)\end{aligned}$$

where AG: total window area per m^2 floor area; AW: total wall area per m^2 floor area; C_1: coefficient for lighting load; C_2: coefficient for small power load; C_3: coefficient for occupants load; Cp_a: specific heat of air (kJ/(kg K)); $\overline{\mathrm{CLF}}$: average cooling load factor for cooling load due to solar heat gain from windows; $h_{fg,0}$: latent heat of evaporation of water (kJ/g); HR_{AC}: the total air-conditioned hours per annum (h); Q_{LGT}: intensity of lighting load (W/m^2); Q_{OCC}: intensity of occupant load (W/m^2); Q_{SPW}: intensity of small power load (W/m^2); ρ_a: density of air (kg/m^3); SC: area weighted shading coefficient of window glasses; $\overline{\mathrm{SHGF}}$: average solar heat gain factor of windows (W/m^2); T_a: indoor design temperature (°C); $\overline{T_o}$: average outdoor temperature (°C); UG: area weighted average heat transfer coefficient of window glasses (W/(m^2 K)); UW: area weighted average heat transfer coefficient of external wall (W/(m^2 K)); VR: fresh air rate per m^2 floor area (L/s/m^2); W_a: indoor design moisture content (kg/kg dry air); $\overline{W_o}$: average outdoor moisture content (kg/kg dry air).

Given that benchmarking is against the same set of year-round hourly, outdoor weather conditions (those of 1989 in Hong Kong, which has been shown to be a representative weather year [48]), it is not be necessary to include the outdoor air conditions ($\overline{T_o}$ and $\overline{W_o}$) as independent variables.

To further simplify Eq. (1), the following assumptions can be made:

(i) $h_{fg,0}$, ρ_a and Cp_a are constants;
(ii) the overall thermal transfer value (OTTV) will be chosen to define the building envelop characteristics in considering that OTTV has been employed to gauge the envelop performance of residential buildings in HK-BEAM 1/99, and the calculation method together with the relevant parameters (e.g. solar factors and equivalent temperature differences) are provided in the document [42,49];

Table 2
Default construction details of HK-BEAM and corresponding China codes requirements

Layer	Material	Thermal conductivity (W/(m K))	Density (kg/m^3)	Specific heat (J/(kg K))	Solar absorptivity	Thickness (m)	
						HK-BEAM	China codes
External walls							
1	Mosaic tile	1.5	2500	840	0.58	0.005	0.005
2	Cement/sand plastering	0.72	1860	840	–	0.01	0.02
3	Heavy concrete	2.16	2400	840	–	0.1	0.3
4	Gypsum plastering	0.38	1120	840	0.65	0.01	0.02
Roofs							
1	Concrete tiles	1.1	2100	920	0.65	0.025	0.025
2	Asphalt	1.15	2350	1200	–	0.02	0.03
3	Cement/sand screed	0.72	1860	840	–	0.05	0.2
4	Expanded polystyrene	0.034	25	130	–	0.05	0.1
5	Heavy concrete	2.16	2400	840	–	0.15	0.4
6	Gypsum plaster	0.38	1120	840	0.65	0.01	0.03
Windows							
1	Tinted glass	1.05	2500	840	0.65	0.006	0.004

(iii) Q_{LGT}, Q_{SPW} and Q_{OCC} will be converted to full load conditions within the occupied hours so that C_1, C_2 and C_3 can be considered as constant coefficients; and
(iv) W_a is constant because there is no control of indoor wet-bulb temperature.

Taking into account the above assumptions, Eq. (1) can be simplified to become:

$$\mathrm{ACL} = (a_0 + a_1(\mathrm{OTTV}) + a_2(\mathrm{VR} \times T_a) + a_3(\mathrm{VR}) + a_4(Q_{LGT}) + a_5(Q_{SPW}) + a_6(Q_{OCC}))\mathrm{HR}_{AC} \quad (2)$$

where a_0 to a_8 are constant terms.

On the basis of Eq. (2), the annual energy use intensity (EUI, kWh/m^2) for air-conditioning of a building can be postulated as:

$$\mathrm{EUI} = \left(b_0 + b_1\left(\frac{\mathrm{OTTV}}{\overline{\mathrm{COP}}}\right) + b_2\left(\frac{\mathrm{VR} \times T_a}{\overline{\mathrm{COP}}}\right) + b_3\left(\frac{\mathrm{VR}}{\overline{\mathrm{COP}}}\right) + b_4\left(\frac{Q_{LGT}}{\overline{\mathrm{COP}}}\right) + b_5\left(\frac{Q_{SPW}}{\overline{\mathrm{COP}}}\right) + b_6\left(\frac{Q_{OCC}}{\overline{\mathrm{COP}}}\right) \right)\mathrm{HR}_{AC} \quad (3)$$

where b_0 to b_8 are constant terms and $\overline{\mathrm{COP}}$ is the average COP of the RAC units.

The equivalent parameters can be determined on the basis of Eqs. (2) and (3). In accordance, VR was converted to L/s/m^2 based upon the physical characteristics of the case study building. Q_{LGT}, Q_{SPW} and Q_{OCC}, and HR_X were converted to full load intensities by taking into account the variations in intensities and profiles between bedrooms and living/dining rooms, and between week-days and weekends. The conversions were done mathematically as shown in Eqs. (4) and (5).

$$Q_X = \frac{Q_{X,L} \times \sum A_{F,L} + Q_{X,B} \times \sum A_{F,B}}{\sum A_{F,L} + \sum A_{F,B}} \quad (4)$$

$$\mathrm{HR}_X = \frac{\mathrm{HR}_{X,L} \times \sum A_{F,L} + \mathrm{HR}_{X,B} \times \sum A_{F,B}}{\sum A_{F,L} + \sum A_{F,B}} \quad (5)$$

where X denotes internal heat gains (LGT: lighting system, SPW: small power equipment, OCC: occupant); HR_X: total hours of operation of "X" per annum (h); $HR_{X,L}$: total hours of operation of "X" per annum at living room (W/m^2); $HR_{X,B}$: total hours of operation of "X" per annum at bed room (W/m^2); Q_X: equivalent intensity of "X" (W/m^2); $Q_{X,L}$: intensity of "X" at living room (W/m^2); $Q_{X,B}$: intensity of "X" at bed room (W/m^2); $A_{F,L}$: area of a living room on one floor (m^2); $A_{F,B}$: area of a bed-room on one basis (m^2).

In accounting for the variations in yearly operating hours, the equivalent intensities in the China codes ($Q_{X,C}$) were hour-weighted against the intensities in HK-BEAM ($Q_{X,H}$) as depicted in Eq. (6):

$$Q_{X,C} = \frac{Q_{X,H} \times \mathrm{HR}_{X,C}}{\mathrm{HR}_{X,H}} \quad (6)$$

Upon the conversions, the original baseline criteria and the equivalent parameters are summarized in Table 3.

7. The baseline building performance

The case study building characteristics were re-defined according to the baseline criteria of the China codes and HK-BEAM for HTB2 and BECRES simulations. The simulated results are referred to as the baseline building performance. Table 4

Table 3
The original baseline criteria and equivalent parameters

Description	Parameter	China codes	HK-BEAM
Indoor design temperature	Temperature (T_a, °C)	**26**	**22**
Envelope features	Heat transfer coefficient (W/(m^2 K))		
	Wall	2.0	3.53
	Roof	1.0	1.97
	Window	6.0	5.89
	Shading coefficient (SC)	0.55 (north) 0.45 (others)	0.65 (all)
	Window-to-wall ratio (WWR)	0.5	0.65
	OTTV (W/m^2)	**12.7**	**18.6**
Occupation densities	Living room (person)	3	2
	Bedroom (person)	2	2
	Q_{OCC} (W/m^2)	**12.02**	**13.46**
Infiltration	Infiltration	7.5 m^3/m^2 AG	0.5 ach^{-1}
	VR (L/s/m^2)	**101.08**	**72.2**
Lighting power intensities	Living room (W/m^2)	7	14
	Bedroom (W/m^2)	7	17
	QLGT (W/m^2)	**2.45**	**14.73**
Small power intensities	Living room	30 (W/m^2)	142 (W/Rm)
	Bedroom	0 (W/m^2)	45 (W/Rm)
	Q_{SPW} (W/m^2)	**7.37**	**5.45**
AC features	COP	2.7	2.4 (≤2.24 Kw)/2.5 (>2.24 Kw)
	$\overline{\mathrm{COP}}$	**2.7**	**2.5**
	Daily operation schedule	1:00–7:00 18:00–24:00 (weekdays) 1:00–24:00 (weekends)	13:00–22:00 (living rooms) 13:00–7:00 (bedrooms)
	Yearly operation schedule	15 May–1 October	1 April–31 October
	HR_{AC} (h)	**2641**	**3072**

Remarks: the equivalent parameters are "bolded".

Table 4
The baseline building performance

Standards	EUI (kWh/m^2)	ACL (kW/m^2)
China codes	41.88	99.01
HK-BEAM	85.68	195.75
Difference (%)	−51.1	−49.4

summarizes the results. It can be seen that the China codes' baseline building energy use, represented by energy use intensity (EUI, kWh/m^2) and the annual cooling load (ACL, kW) are 51.1% and 49.9% lower than that of HK-BEAM. Considering that the China codes allow 15% deviation from the codes' requirement [25] (i.e. EUI = 41.88 $\times$ 1.15 = 48.2 kWh/m^2), this indicates that the HK-BEAM baseline building (EUI = 85.68 kWh/m^2) cannot satisfy the China codes' minimum requirements.

Other than the simulation results, a review of the design characteristics of 22 HK-BEAM certified residential towers (Table 5) indicates that individual design criterion including T_a, COP of the RAC units, SC and WWR of almost all certified buildings are unable to satisfy the China codes' requirements.

Whilst both the individual design criterion and the collective influence of all criteria point to the fact that HK-BEAM certified buildings cannot satisfy the China codes' minimum requirements, there is a need to evaluate the relative impact of individual criterion on EUI and ACL, and to identify the non-conforming criterion. This can be done by using the HK-BEAM baseline building as a baseline case. The evaluation is done by varying the baseline case's characteristics according to the China codes in turn. For each simulation run, only one design criterion is varied and all other characteristics of the baseline case are retained.

The change in EUI (∂EUI) and ACL (∂ACL), with respect to the incorporation of various criteria of the China codes are summarized and ranked in Table 6. The change varies from a positive number to a negative number. A positive number implies that the corresponding criterion in the China codes is less stringent than the same criterion in HK-BEAM, and vice versa for a negative number. It can be seen that the China codes set more stringent requirements for T_a, HR_{AC}, OTTV, Q_{OCC}, COP of RAC units and Q_{LGT} whilst HK-BEAM sets higher standards for Q_{SPW} and VR. The influence of higher T_a and smaller HR_{AC} in the China codes corresponds to 26% and 24% reduction in EUI, whilst better envelop design accounts for another 9.7% drop in EUI.

8. Sensitivity analysis

Given the influence of various criteria are magnitude-dependent, the established equivalent parameters offer a convenient way of assessing the relative impact of each criterion on EUI and

Table 5
Design characteristics of 22 HK-BEAM certified residential towers

Building	Major orientations	T_a (°C)	COP	WWR	SC	EUI (kWh/m^2)	
						Design	Baseline
1	NW/SE	22	2.67	0.62	0.74	93.4	114.6
2	SW/SE/N	22	2.5	0.63	0.65	93.5	108.3
3	SE/NE/W	22	2.5	0.63	0.65	100.8	104.6
4	NE/NW/S	22	2.5	0.63	0.65	92.6	107.4
5	SE/S/E	22	2.5	0.63	0.65	91.5	104.7
6	E/SE/NE	22	2.5	0.63	0.65	96	104.9
7	E/W	24	2.5	0.65	0.96	95.1	98
8	E/W	24	2.5	0.65	0.96	98	101.4
9	E/W	24	2.5	0.65	0.96	93.3	97.4
10	E/W	24	2.5	0.65	0.96	83.2	87
11	SE/SW	22	2.67	0.46	0.71	115.3	144
12	SE/SW	22	2.67	0.46	0.6	119.4	144
13	SE/SW	22	2.67	0.46	0.96	123.4	144
14	W	22	2.54	0.61	0.65	104.9	128.2
15	W	22	2.54	0.61	0.65	80.9	95.5
16	W	22	2.54	0.61	0.65	77.7	95.6
17	W	22	2.54	0.61	0.65	58.8	72.3
18	S	24	3	0.42–0.75	0.95	88.2	101.3
19	S	24	3	0.42–0.75	0.95	81	95.1
20	SW	24	3	0.42–0.75	0.95	98.7	113.4
21	SW	24	2.8	0.31	0.65	81.8	84.1
22	SW	24	2.8	0.31	0.65	81.9	84.2
Average		22.8	2.63	0.57	0.77	93.2	105.9

Table 6
Relative impact of various criteria

Parameter		∂EUI		∂ACL		S_{EUIx}	S_{ACLx}	Rank	
X	∂X	kWh/m^2	%	kW/m^2	%			∂EUI (∂ACL)	S_{EUIx} (S_{ACLx})
T_a	4	−22.56	−26.33	−54.13	−27.65	−1.45	−1.52	1 (1)	2 (1)
HR_{AC}	−431	−20.79	−24.23	−37.34	−19.08	1.73	1.36	2 (2)	1 (2)
OTTV	−5.9	−8.30	−9.68	−28.65	−14.63	0.31	0.46	3 (3)	4 (3)
$\overline{COP}$	0.2	−4.77	−5.57	0	0	−0.70	0	4 (–)	3 (–)
VR	28.88	3.73	4.34	8.18	4.18	0.11	0.10	5 (5)	7 (6)
Q_{SPW}	1.92	3.59	4.16	7.77	3.97	0.12	0.11	6 (6)	6 (5)
Q_{LGT}	−12.28	−3.41	−3.98	−14.39	−7.35	0.05	0.09	7 (4)	8 (7)
Q_{OCC}	−1.44	−1.18	−1.38	−7.21	−3.68	0.13	0.34	8 (7)	5 (4)

ACL. This can be quantified by the sensitivity values (S). The sensitivity values, mathematically, can be represented as:

$$S_{\mathrm{EUIx}} = \frac{\partial \mathrm{EUI}}{\partial X}\frac{X}{\mathrm{EUI}} \quad \text{and} \quad S_{\mathrm{ACLx}} = \frac{\partial \mathrm{ACL}}{\partial X}\frac{X}{\mathrm{ACL}}$$

where S_{EUIx} and S_{ACLx} are the sensitivity values for parameter "X"; ∂EUI and ∂ACL are changes in EUI and ACL with the China codes criterion implemented; and ∂X denotes the change in equivalent parameter.

Sensitivity values for all the equivalent parameters have been determined and ranked according to their degree of influence as summarized in Table 6. It can be seen that T_a, $\mathrm{HR_{AC}}$, OTTV, and COP of RAC units continue to be the most influential parameters such that EUI is most sensitive to their changes. The influence of the other parameters is smaller, and Q_{LGT} has the smallest influence. Similar ranking is observed for ACL; except that COP has no influence, and the ranking between T_a and $\mathrm{HR_{AC}}$ has been reversed. The reverse in ranking can be explained by partial derivative of ACL and EUI (Eqs. (2) and (3)) with respective to T_a and $\mathrm{HR_{AC}}$.

It is also noted that the S_{ACLx} values are slightly larger than S_{EUIx} values. This is reasonable because RAC units are only equipped with simple on-off capacity control to lower the energy efficiency at low load conditions [50]. Hence, an increase in cooling load does not proportionally increase the energy use.

9. Conclusions

The characteristics of the China codes and the Hong Kong codes have been reviewed in this study. For the purpose of benchmarking the China codes against HK-BEAM, the energy use and the annual cooling load of a case study building, based upon the corresponding compliance criteria, have been determined by simulation methods. The results show that the case study building in compliance with the China codes will consume 51.1% less than that of HK-BEAM. This confirms the effectiveness of the China codes in controlling the energy use of residential buildings in the hot summer and warm winter zone; and indicates that HK-BEAM certified buildings may not satisfy the China codes requirements. This observation agrees with the actual design characteristics of 22 residential towers in Hong Kong.

The equivalent parameters were established for direct comparison with the compliance criteria stipulated in the China codes and in HK-BEAM. The influence of each compliance criterion on the annual cooling load and the energy use intensity has been quantified by sensitivity analysis. The analysis reveals that the energy use for air-conditioning and the annual cooling load are most sensitive to the default air-conditioning operation hours, indoor design temperature, COP of the RAC units and the envelop characteristics.

Given Hong Kong's sovereignty has been returned to China, the results provide a good reference should reciprocal recognition of the China codes and HK-BEAM be considered in the future.

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