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Envelope performance of residential building in cool, warm and hot climatic zones: Results from self-designed in-situ monitoring campaigns

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ABSTRACT

Climatic conditions can exert significant impacts on energy demand of residential buildings. Therefore, case-based evidence is necessary for aiding local policy making on building energy performance. By designing and carrying out in-situ monitoring campaigns respectively in Cambridge, Hong Kong and Shanghai, we present in this paper a cross-regional analysis of actual building envelope performance in these three climatic regions that operate under different energy efficiency policies. Compared with conventional tabulated data, information gleaned from the method of in-situ monitoring shows lower uncertainty and higher precision, especially when the wall has good thermal properties. By comparing practices in different regions and with accurate post-occupancy thermal data, the analytical results further show that the effectiveness of building-related policies on energy performance varies across regions. This is one of the pioneering studies that make interactive policy recommendations based on the evidence obtained from cross-regional, in-situ monitoring campaigns.

1. Introduction

Residential buildings consume over 25% of total primary energy on an annual basis in many modern cities around the world [1,2]. This makes the reduction of residential building emissions one of the key components of overall global carbon reduction strategies [3]. Building regulations have thus been developed to ensure the energy performance of building envelopes so that the energy demands of space conditioning systems can be controlled. Indicators of envelope performance – represented mainly by the thermal transmittance (U-value) and the overall thermal transfer value (OTTV) – are subsequently introduced. The former is referenced by the United States, many European countries, and mainland China, whereas the latter is adopted among major Southeast Asian countries. However, it must be acknowledged that residential envelope practice may vary across different countries and regions due to factors such as climate differences and distinct local experiences. Policies with regard to the energy demands of buildings therefore risk being formulated upon insufficient evidence or antiquated metrics that only integrate the past local experience [4]. On this note, it is crucial to examine the up-to-date envelope performance of residential buildings in different geographical locations to better inform the evidence-based decision-making process for local policymakers. With the accumulation of pertinent data, a fully-fledged interactive policy framework can also be developed, absorbing successful local experiences and being more robust and resilient to respond to potential risks stemming from climate change and demand fluctuations.

In the existing literature, models and simulation tools have been developed to assess building energy demand by specifically comparing the energy consumption rates between pre- and post-implementation phases of sustainable construction and retrofit strategies [5]. Unfortunately, Disarrayed performance results are often generated due to the limitations inherent in some conventional building energy assessment methods that generally rely on visual inspections, empirical assumptions, tabulated data and numerical calculations [6,7]. The resultant evaluative gaps and errors are likely to lead to the adoption and implementation of inappropriate or ill-fitting energy efficiency measures. More accurate assessment approaches based on adequate current building data are therefore warranted [7]. Particularly for completed buildings, in-situ monitoring can be performed without the utilization of many visual inspections, assumptions, and tabulated data [8]. Because of this advantage, in-situ monitoring of the thermodynamic parameters of building elements (e.g., R-value and U-value) has been developed and used more often over the past

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Nomenclature

C	Thermal mass of the wall, J/m^{2}K
$OTTV$	Overall thermal transfer value, W/m^2
p	Current time step
$p + 1$	Next time step
Q_{in}	Heat flux is the rate of heat energy transfer through a given element per unit surface at the current time, W/m^2
Q'_{in}	Heat flux is the rate of heat energy transfer through a given element per unit surface at a future time, W/m^2
R	R-value is a measure of thermal resistance used in the building, m^{2}K/W
R_1, R_2	Wall thermal resistances estimated by the STM, m^{2}K/W
R_{si}	Internal surface thermal resistances of the wall, m^{2}K/W
R_{so}	External surface thermal resistances of the wall, m^{2}K/W
R_w	Total wall thermal resistances excluding surface resistance, m^{2}K/W
T_{mass}	Temperature of the thermal mass estimated by the STM, °C
T_{si}	Temperature of the internal wall surface at the current time, °C
T'_{si}	Temperature of the internal wall surface at a future time, °C
T_{so}	Temperature of the external wall surface at the current time, °C
T'_{so}	Temperature of the external wall surface at a future time, °C
U-value	U-value is the heat transmittance of a building element, W/m^{2}K
τ	Time step is the time between two data readings (5 min in this paper), s

few years to carry out building energy assessments in a more accurate manner.

In this paper, our analysis is backed up by the data obtained from three in-situ monitoring campaigns conducted in three cities with different climatic zones, including Cambridge, Hong Kong and Shanghai. The ultimate purposes are threefold. First, we hope to discover and quantify the potential U-value estimation differences in differing geographical conditions, and to subsequently determine the climate impacts on wall structures' thermal performance. Then, the measured results will be applied to evaluate the vulnerability of the current policies by predicting their potential influence on building energy demand under possible climate-change scenarios. Most importantly, based on the monitoring evidence and predictions, we strive to put forth not only regionally interactive recommendations to the three cities under study, but also an overall policy framework to assist in the development of future energy-saving policies that suit jurisdictions under vastly different climatic conditions.

2. Background of policies and regulations that affect energy performance of building envelope

It is widely known that current GHG emissions may lead to a global environmental crisis and all major economies should spare no effort to maintain sustainable development [9]. To tackle the problem of climate change due to excessive GHG emissions, the governments of England, Hong Kong and Shanghai have enacted strategies to control the energy demands of buildings. In 2008, the U.K. government committed to reducing its GHG emissions by 80% (based on the 1990 levels) before 2050 [10]. To achieve this goal, in the British Building Regulation 2010 Part L1B, one of the criteria for energy status improvement, an existing English dwelling must upgrade its external wall to a maximum of 0.70 W/m^{2}K in thermal transmittance (U-value) if it was originally determined to have poor energy efficiency [11]. At the present time, one of the most common building characteristics measuring the energy performance of the building envelope is the U-value, which is the thermal transmittance of building elements. The U-value is indicative of the rate of heat loss through a building material; hence, it specifies the effectiveness of energy conservation for a particular room or building [12]. Therefore, the heating and cooling loads for the design of ventilation and air-conditioning systems in many building construction and retrofit projects will be closely related to the U-values [13]. Similar to the case of England, the U-value in Shanghai is limited to 1.00 W/m^{2}K for the newly constructed walls of residential buildings [14]. Instead of limiting the maximum U-value, as is the case with general Chinese building regulations, Hong Kong has chosen to regulate another common building parameter, the overall thermal transfer value (OTTV), for the purpose of determining the overall thermal performance of the building envelope [15]. The OTTV for walls calculates an average heat transfer rate of a building through opaque walls and window glasses, which is affected by the component U-value, the surface area of walls and windows, the shading features, and the equivalent temperature. According to the Buildings Department of Hong Kong [16], the current OTTV threshold for residential walls is 14 W/m^2.

To ensure that government policies are properly implemented, comparisons of estimated energy consumption pre- and post-retrofit are essential. Therefore, in-situ monitoring, which measures real building thermal characteristics, can play an important role in the assessment of building energy performance, especially for supporting projects that require a detailed and accurate understanding of the relevant properties. As one of the pilot studies that conduct cross-region monitoring campaigns in three climate zones, this paper provides evidence-based suggestions to the development of local energy-efficiency policies for residential buildings.

3. Method and monitoring design

3.1. Design of in-situ monitoring campaigns

This paper makes policy suggestions based on the evidence from in-situ monitoring results. The monitoring campaigns collected primary data from three residential buildings located in three climatic zones, which are referred to as Residence 1 in Cambridge, Residence 2 in Hong Kong and Residence 3 in Shanghai. The rooms tested remained unoccupied during the monitoring period so as to avoid any disturbances from user activities. In Residence 1, a two-story house in Cambridge, U.K.which is in the cool humid climate zone, the project measured the north-facing cavity insulted wall on the second floor. The house was not occupied at the time, and all of the furniture had been removed. The wall, which was 273 mm thick overall, was in the northeast room on the first floor. Its structure, from outside to inside, consisted of 110 mm exposed brick, a 50 mm cavity filled by foamed plastic insulation material, a 100 mm internal concrete block and 13 mm of plaster. The total analysed data were collected over a continuous 92-day period from

March to June of 2015 (19.6 °C for the average temperature and 55 mm for the monthly precipitation in the measured period). In Residence 2, the measured room was in an apartment building in Hong Kong, a city belonging to the very hot and humid climate zone. Completed in 1996, the building had a north-facing wall consisting of 10 mm gypsum plaster, a 125 mm concrete wall, a 10 mm cement/sand render and 5 mm mosaic tiles. The monitoring campaign lasted 126 days from April to August of 2018 (30.32 °C for the average temperature and 284 mm for the monthly precipitation in the measured period). A residential building in Shanghai was selected as Residence 3. Situated in a city with a warm and humid climate, the building started operating in 2007 and was in relatively newer condition compared to the other two buildings. The selected wall also faced north, and its structural layers included 15 mm cement plaster, 200 mm concrete wall, 30 mm expanded polystyrene and 60 mm concrete. The wall was monitored for a 98-day period between May and August of 2019 (28.60 °C for the average temperature and 118 mm for the monthly precipitation in the measured period). A summary of the three selected residences is shown in Table 1.

The three monitoring campaigns followed the standard procedures of measuring thermal transmittance (U-value) instructed in ISO 9869: 2014 [18]. The monitoring process used a heat flux meter (HFM) to measure the heat flux density through the wall [19]; the meter was placed on the internal wall surface. Near the HFM, two type-T surface thermistors were installed opposite to each other on both the internal and external wall surfaces. All data measured by the above instruments averaged over five minutes and were recorded by two Eltek 450 data loggers.

So far, admittedly, it is still unclear how likely an error can be caused by thermal radiation sources inside the building (e.g., solar radiation penetrating through the windows and infrared radiation from space heating radiators). For the in-situ U-value monitoring, the direct radiation is bound to increase both the internal wall surface temperature and the heat flux density from inside to outside [20]. In addition to selecting the north-facing walls for monitoring to avoid direct sunlight, the internal radiation sources such as the space heating radiator were also kept off and blocked by aluminium foils.

3.2. U-value estimation using the single thermal mass (STM) model

The in-situ U-value is conventionally estimated using the average method (AM). According to the ISO standard [18], by assuming that there is a steady-state heat transfer process through the wall, the U-value can be calculated by averaging the measured internal and external surface temperatures and the heat flux density over a long period to cancel out the storage effect of the thermal mass:

$$U = \frac{1}{\frac{\sum(T_{si}-T_{so})}{\sum(Q_{in})} + R_{si} + R_{so}} \tag{1}$$

Because of the fluctuation of the internal and external temperature and the presence of a thermal mass, it can take over a week to acquire satisfactory U-value estimations through the AM [7,21]. Furthermore, the assumption of steady-state heat transfer implies that the measurements are taken when the internal and external surface temperature difference is greater than 10 °C [22]. These time and seasonal restrictions in the AM suggest that improvements are needed to the U-value estimation model.

This paper implemented the novel single thermal mass (STM) model with the Bayesian prediction technique to estimate the U-value by virtue of the in-situ monitoring data. This approach was initially developed by Biddulph et al., who proved the good accuracy and efficiency in estimating the U-value of building envelopes in the U.K. [23]. As shown in Fig. 1, the STM model takes into account an effective thermal mass point inside the wall so as to model the involved building parameters more comprehensively. Recent studies have further extended the number of estimated thermal mass layers to 2TM, and found close accuracy for the U-value estimations [24]. However, as more unknown parameters are in the function, the explanatory power of parameters will be reduced. Therefore, in the monitoring design in this paper, the STM model is more suitable with a limited amount of measured data. In the model, four unknown parameters are created in the STM model: the inner and outer thermal resistance (R1 and R2), an effective thermal mass (C) and the initial temperature at the effective thermal mass point (T_{mass}^{init}). With the knowledge of the thermal mass temperature (Tmass) at the current time step (p), the following equation (Eq2) can be used to predict the thermal mass temperature at the next time step (p + 1) (i.e., after one time step in duration, or τ).

$$T_{mass}^{p+1} = \frac{\frac{T_{si}{}^{p+1}}{R_1} + \frac{T_{so}{}^{p+1}}{R_2} + C\frac{T_{mass}{}^{p}}{\tau}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{C}{\tau}} \tag{2}$$

For each time step, the calculated thermal mass temperature can then be used to predict the corresponding heat flux density through the wall (Q_{in}^{p}):

$$Q_{in}^{p} = \frac{T_{si}{}^{p} - T_{mass}{}^{p}}{R_1} \tag{3}$$

The model uses the Bayesian analysis technique to determine the best-fit combination of the four parameters (i.e., parameters enabling the chi-squared function are set at the minimum) which can reproduce the heat flux density in the monitoring process. Thus, the U-value is determined using the two resistance values (R1 and R2) of the four best-fit parameters. Since the internal and external surface thermistors were used in the specific monitoring campaigns of the project, the U-value took into account constant internal and external surface thermal resistances (R_{si} and R_{so}), which refer to the tabulated values suggested by the local standards. The adjusted U-value calculation method can be expressed by Eq. (4):

Table 1
Basic information of the three residences for the in-situ monitoring campaigns.

Name	Location	Construction year	Climate zone*	Wall structure
Residence 1	Cambridge	Before 1990	5A Cool Humid	13 mm gypsum plaster + 100 mm aerated concrete block + 50 mm foamed plastic insulated cavity + 110 mm exterior brick
Residence 2	Hong Kong	1996	1A Very Hot Humid	10 mm gypsum plaster + 125 mm concrete wall + 10 mm cement/ sand render + 5 mm mosaic tiles
Residence 3	Shanghai	2007	3A Warm Humid	15 mm cement plaster + 200 mm concrete wall + 30 mm expanded polystyrene + 60 mm concrete

*The categorisation of climate zones refer to the ANSI/ASHRAE/IES Standard 90.1-2016 [17].

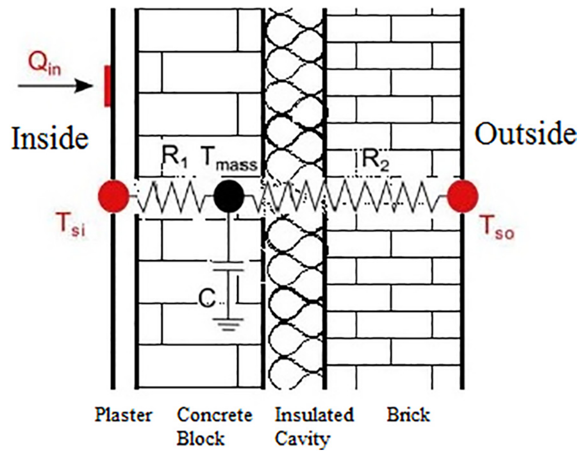

Fig. 1. Diagram of an exemplary wall structure and the principle of the single thermal mass (STM) model which contains the four unknowns (the black labels) and the measured parameters (the red labels). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$U = \frac{1}{R_{Total}} = \frac{1}{R_1 + R_2 + R_{si} + R_{so}} \tag{4}$$

4. Result from in-situ monitoring

4.1. Recorded thermal conditions

Climate differences could be a key cause of the different thermal performance measures of the walls in the three locations. Assessing the thermal conditions in the three monitoring time periods would therefore be an essential prior step of evaluating the regional features of each building envelope. To calculate the U-values of the three wall structures, the temperatures of both the internal and external wall surfaces were recorded throughout the entire monitoring period. It should be noted that heat flux, which determines the rate of energy loss through the walls, is also an important parameter measured in the campaigns. The recorded data have been summarised in the following boxplot charts (Fig. 2).

From the chart, it can be seen that in each of the three residences, the average internal surface temperature was higher than the external surface temperature; it is possible that this was caused by the heat gains, such as solar radiation and human activities in neighbouring apartments. The temperatures of the external surfaces also varied more greatly, resulting in an average standard deviation (s.d.) of 5.42 compared with the average s.d. of 2.51 for the internal surface temperature. The phenomenon of a steadier temperature being measured in the indoor space may result from the thermal mass effect of the building envelope, which moderates the thermal exchange with the outdoor environment.

Residence 1 had a lower average surface temperature than the other two residences, which is a reflection of the cooler climate pattern for the U.K. Although Residence 2 was located in the hot climate, the average temperatures for both the internal and external surfaces were 31.01 °C and 30.32 °C, respectively, which were only slightly greater than those for Residence 3 in the warm climate (29.56 °C and 28.63 °C, respectively). However, the close temperature conditions between Residence 2 and 3 did not lead to similar heat flux recordings; the average heat flux for Residence 2 was 6.87 W/m^2, which was much higher than the 0.82 W/m2 for Residence 3. Moreover, the heat flux also fluctuated more significantly (within a range of over 70 W/m^2) in Residence 2 when compared with the other two buildings. These values may imply the lower thermal insulation performance of Residence 2. The heat flux values of Residence 1 remained in the middle of the three at 2.57 W/m^2 on average. It was also apparent that the heat could transfer in both directions for all three of the residences (a positive heat flux indicates that heat flows from the internal to the external space, and vice versa), proving the effectiveness of the thermal mass effect of the wall structures. In addition, the outliers (empty dots) for all of the thermal conditions were probably caused by the sudden changes of the environment, such as local heat waves and strong typhoon events. Since the measurements were taken over the course of months, the effects of short-term extreme weather changes were relatively minimal with respect to the estimation of U-values.

4.2. Estimation of U-values from in-situ monitoring

With the application of the STM model, the overall U-values estimated for Residences 1, 2 and 3 were estimated. The U-value evolution curves for the three residences are shown in Fig. 3. It should be noted that the U-value of the monitored wall in Residence 2 was much higher than that of the other residences. This is perhaps due to the lack of regulations that directly limit U-

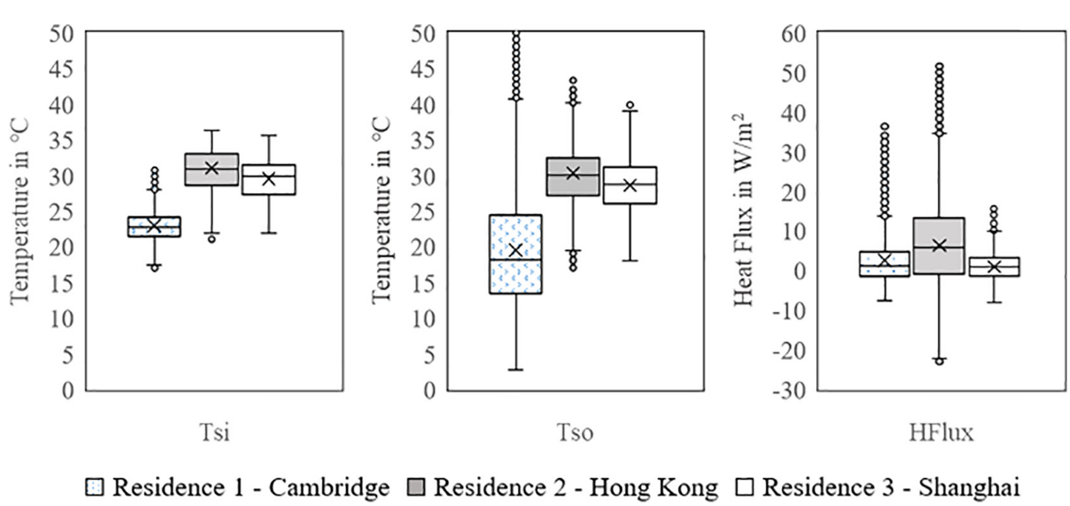

Fig. 2. The thermal conditions of the three monitored residences for U-value estimation (Tsi: internal surface temperature, Tso: external surface temperature, and HFlux: Heat flux).

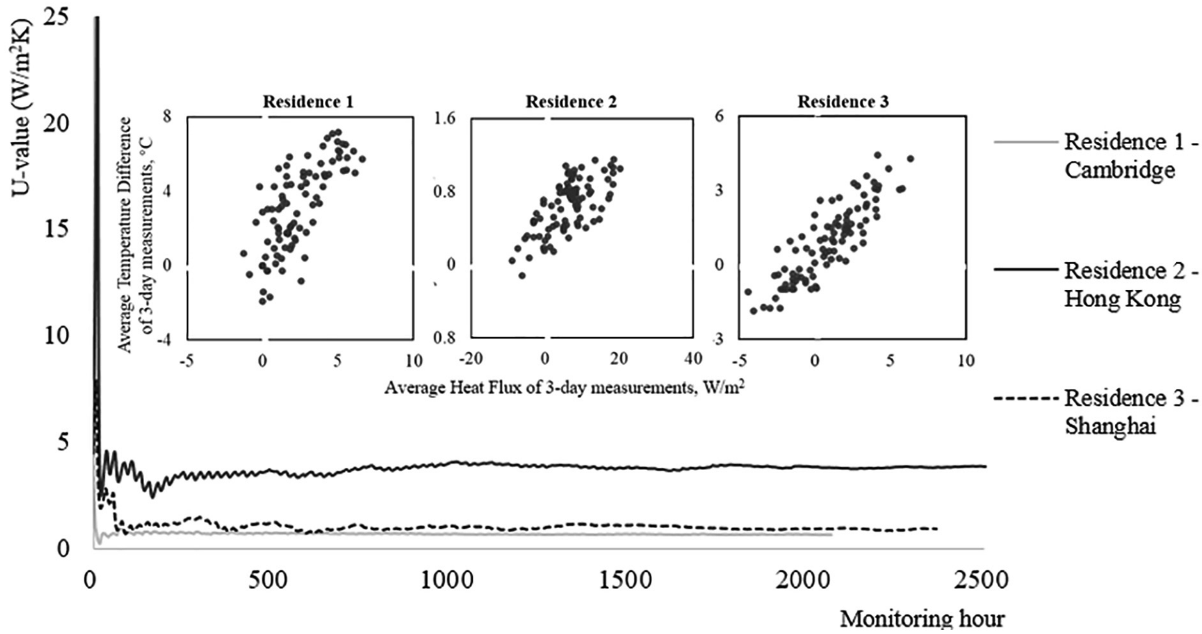

Fig. 3. The U-value evolution curves for the three residences and the correlation between the average three-day internal/external temperature difference and the corresponding average heat flux.

values in Hong Kong. For the house in Cambridge with the lowest estimated U-value, the filled cavity wall structure demonstrates the good performance of thermal insulation. For Residence 3 in Shanghai, which was completed only for a short time, the monitoring result verified compliance with the local U-value regulations as under 1.00 W/m^{2}K. Although all of the evolution curves oscillate greatly at the beginning due to the limited knowledge of thermal mass effect, they start to stabilise within 72 h of measurement. If considering the point in time at which the U-value varies by less than 5% within the previous 24 h as the stopping time [18], the stopping times for Residences 1, 2 and 3 were 8.8 days, 9.0 days and 10.7 days, respectively. This result proves the appropriateness of recommending a two-week monitoring campaign in accordance with ISO standards [18]. In addition, the monitored data may also have implications for assessing the correlations between the basic parameters (temperature and heat flux) and empirical thermal performance in an exemplary building in each city. According to Eq1, for a relatively long monitoring period (over three days), the U-value may be proportionally correlated with the ratio of $\sum(T_{si} - T_{so})$to$\sum(Q_{in})$ when assuming the thermal resistance of the internal and external surfaces is constant. This may explain the correlation between $\sum(T_{si} - T_{so})$and$\sum(Q_{in})$ shown in Fig. 3. For each monitored wall structure, the average temperature difference between the internal and external wall surface was positively correlated with the average heat flux. In Residence 2, this correlation was the strongest, indicating that a small temperature difference can result in a large heat flux through the wall. This result also implies that there was decreased thermal insultation performance for the wall in Residence 2.

4.3. Error analysis and comparison with tabulated U-values

The measurement results are interpreted by an error analysis. The errors and uncertainty of the U-value monitoring can be resulted from the following factors. Firstly, statistical modelling error and standard deviation of U-values in the whole U-value estimation period (i.e. the variation in U-values when measuring under different internal and external conditions) [23] may cause direct U-value deviations during the calculations, and they can be expressed in δU_{stat} and $\delta U_{s.d.}$. Furthermore, uncertainty of the measuring instrument can also result in errors, which were expressed in δq, δT_i and $\delta T_o$for errors in heat flux meter, internal and external surface thermistors respectively. For each parameter, the error due to the minimum output of the data logger is included according to the Step E2.4 in ISO 9869: 2014 [18]. Finally, this paper used the reference values in ISO 9869: 2014 (ISO, 2014), 5%, for contact error, since the collection of its specific value is difficult from the acquired data and information. ISO 9869: 2014 also noted an error source due to time variation.This error, nonetheless, should be much smaller as all of the three monitoring campaigns lasted significantly longer (>3 months) than the suggested monitoring period (2 weeks). In summary, as there is no explicit evidence for any dependence between these error factors, they are assumed to be independent from each other. The total uncertainty of estimated U-value can be expressed in the following equation [25]:

$$\delta U = U \times \sqrt{\left(\frac{\delta U_{stat}}{U}\right)^2 + \left(\frac{\delta U_{s.d.}}{U}\right)^2 + \left(\frac{\delta q}{q}\right)^2 + \left(\frac{\delta(T_i - T_o)}{T_i - T_o}\right)^2 + (5\%)^2} \tag{5}$$

When the STM model was applied, the overall U-values estimated for Residences 1, 2 and 3 were estimated. 0.630 ± 0.002^{stat} W/m^{2}K, 3.804 ± 0.005^{stat} W/m^{2}K and 0.823 ± 0.001^{stat} W/m^{2}K, respectively. The small statistical error means that the estimated set of parameters fits the total recorded dataset well. In addition to determining the statistical error, this research project has also examined systematic errors, including uncertainty in the instruments (5% for HFM, ±0.1 °C for the thermistors, and 0.083 mV for the data logger), contact errors between the HFM and the internal wall surface (5% according to ISO [18]) and the thermal resistance of the HFM plate (less than 0.0007 m^{2}K/W[19]). Applying Eq5, the estimated U-values for the three monitoring campaigns can be expressed as 0.63 ± 0.06$^{stat+sys}$ W/m^{2}K, 3.80 ± 0.46$^{stat+sys}$ W/m^{2}K and 0.82 ± 0.08$^{stat+sys}$ W/m^{2}K.

During the conventional architectural design stage when in-situ monitoring is not possible, the U-values of the wall structures can be calculated from the material thermal property (mainly the tabulated conductivity) and layer thickness. If the U-value were estimated using tabulated data, its range would be derived from the conductivity range of each layer of material [14,26,27]. Fig. 4 compares the estimated wall U-values in the in-situ monitoring campaigns with the tabulated U-values for the three residences.

In general, the U-values estimated under both methods delivered similar results, which proves that all of the three selected walls have performed well following the designed ability of thermal insulation. The monitoring results of both Residence 1 and 3 have kept the U-value uncertainty interval within 10%, which is approximately 40% narrower than the U-value range from the tabulated data. However, for Residence 2, there was a challenge with respect to accuracy for the estimation from in-situ monitoring due largely to the poorer thermal insulation qualities. Apart from that, ISO 9869: 2014 [18] gives a suggestion that the general well-designed in-situ U-value measurement may roughly have an uncertainty ranging from 14% to 28%, which is higher than the estimated uncertainty in this monitoring campaigns for Residences 1 and 3. One of the differences in the two uncertainty estimations is attributable to the seasonal effect. ISO suggests that a 10% uncertainty can be ascribed to the daily and seasonal environment variation. This variation, reflected by the standard deviation of the quarter-year measurements, is culpable for an approximately 7% uncertainty in our study.

Overall, the monitoring method following ISO 9869: 2014 have shown its good applicability in this paper, despite that performance gaps between tabulating and monitoring approaches are not clear in the three cases concerned. Similar with the initial study on a solid wall in the U.K. [23], the STM method has done an accurate and efficient estimation of U-value in the filled cavity wall in Residence 1, showing the wide application of this method in the cool climate. Moreover, the STM method is also proven adaptive in warm and hot climate zones in the face of a slightly higher uncertainty in the thin wall of Residence 2 due possibly to a small thermal mass.

4.4. Insulation matters: Decomposition analysis of U-values in the three monitoring campaigns

Ultimately, it can be said that the three studied walls performed differently from the lens of the U-values discussed in the previous parts of the paper. The main reason behind the U-value differences is the wall structures, which could only be investigated by decomposing the wall layers. Using temperature changes as an indicator of insulation performance, the following analysis splits the entire system into nodes, consisting of indoor and outdoor nodes, internal and external surface nodes and the layer node at each junction of wall materials.

Fig. 5 presents the temperature gradients in the three wall systems. It shows that in Residence 1, over 90% of the temperature drop occurred between the second and third wall layers, which represents the insulation layer made of 50 mm foamed plastics. With a conductivity value of 0.04 W/mK on average, the insulation layer generated 1.25 m^2K/W of thermal resistance, which effectively reduced heat loss to the outdoor environment. Located in a warm climate, Residence 3 was also formed by walls with effective insulation layers between their second and third nodes. The insulation layer was made of expanded polystyrene of 30 mm in thickness, which generated 1.17 m^2K/W of thermal resistance. This layer was responsible for the majority of the temperature drop, though the magnitude was slightly smaller than that of Residence 1. Unlike Residences 1 and 3, the wall for Residence 2 did not have a clear insulation layer with a thermal resistance greater than 0.10 m^2K/W, resulting in the largest temperature drop that appeared in the thin air layer near the internal surface. The much higher U-value of the monitored wall in Residence 2 was therefore in large part caused by the lack of an effective insulation layer. Furthermore, since the thermal resistance of the surface could be affected by the local air movement, the overall wall performance would be more unstable, leading to greater heat flux fluctuation and more U-value uncertainty during the measurement period. This highlights the crucial role that the insulation layer plays in ensuring the overall thermal performance of the wall system.

In retrospect, policy intervention may be a key cause of the difference in energy performance for the envelopes of each of the three residences. Both the U.K. and Shanghai have legislations that directly stipulate the maximum U-value limits, leading to the necessity of using insulation materials. When When comparing the thresholds of the two regions, Residence 1 has a lower U-

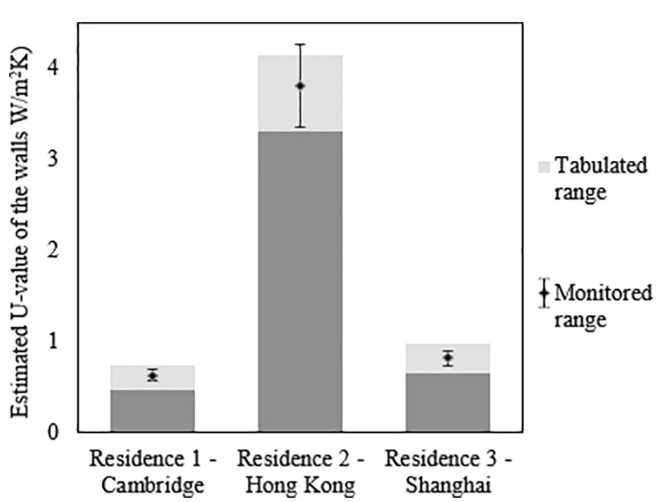

Fig. 4. Comparison of the U-values estimated based on monitored and tabulated data.

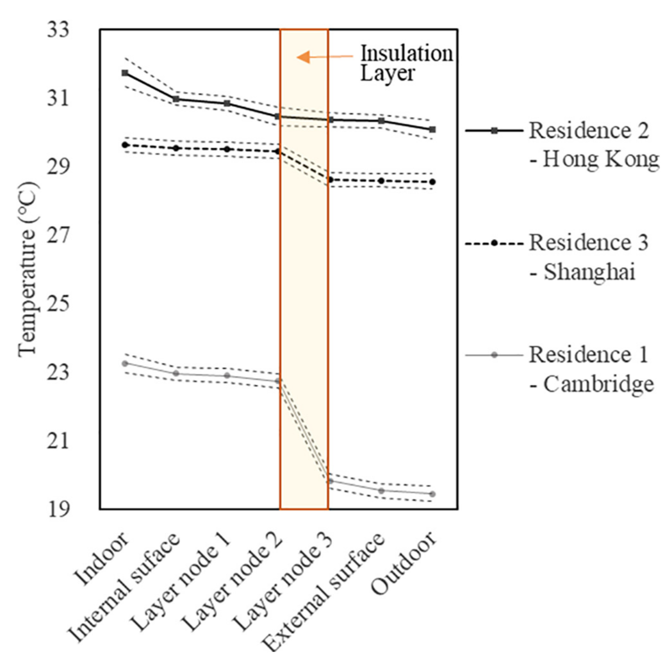

Fig. 5. Temperature gradients through the nodes of the three wall systems Note: the ranges between the dotted lines show the temperature uncertainty in the estimation of thermal resistances.

value (0.70 W/m2K) limit. As with the U.K., as well as other places in a cooler climate like Norway and Germany, it seems to be a common practice to introduce stricter U-value regulations to save energy for space heating. In warmer cities like the majority of those in eastern China, the U-value threshold tends to be more moderate, and there is no mandatory requirement for existing buildings to conduct insulation upgrades at the present time except in Shanghai where installing an insulation layer in a new wall is a common practice in many buildings to meet the local U-value requirements. When it comes to some places in hotter climates such as Hong Kong and Malaysia, however, the OTTV legislations are used in lieu of the direct U-value limiting codes. The OTTV legislations control overall envelope performance while also allowing for high U-value envelopes to be constructed. In these places, an insulation layer is often not required to meet the maximum OTTV thresholds, and this might be the reason that there is significantly poorer thermal performance in the wall structure in Residence 2. In addition, while space heating is usually not needed in Hong Kong, a well-insulated building can considerably reduce the energy demand for space cooling in the hot seasons. According to an energy end use survey [28], energy consumption for space cooling accounts for 35% of all the residential energy end-uses in the past decade; this figure can be compared with the 22% allocated for space heating that was recorded on an English household survey [29]. The high energy consumption of space cooling not only brings a resultant high energy intensity in residential buildings, but also increases energy imbalance and vulnerability due to different seasons, evidenced by the fact that residential buildings in the city during the high-AC season (May to October) consume 71% more electricity than the corresponding rates during the low-AC season (November to April) [15]. Energy conservation in space conditioning can thus be achieved in Hong Kong if more attention is paid to the promulgation of strict legislations regarding envelope energy performance.

5. Policy vulnerability due to the impact brought about by climate change

5.1. Projected data of local climate change

The Intergovernmental Panel on Climate Change [30] reported that global climate warming caused by human activities reached approximately 1 ± 0.2 °C above the pre-industrial levels in 2017, and that the temperature could increase by 0.2 °C per decade. This anticipated continuing temperature rise in the future may influence the building energy demands of space conditioning, and the impact of envelope performance will be contingent upon each building's characteristics, such as the location and the U-value. This section incorporates the projected scenarios of local temperature changes into our framework to study their impact on energy demands for the three selected rooms.

Representative Concentration Pathways (RCPs) is an extensively adopted system predicting the pathways of climate change in scenarios where the radiative forcing values span from 2.6 W/m^2 (RCP2.6) to 8.5 W/m^2 (RCP8.5) [31]. RCP2.6 represents a scenario in which the world, through significant effort, is able to implement sizeable reductions in the emissions of GHG. In contrast, RCP8.5 represents a scenario in which GHG emissions keep increasing throughout the world. Based on these scenarios, countries and regions have made local projections for the future with respect to temperature changes. Table 2 summarises the projected temperatures in the regions of the three residences in both 2030 and 2050.

By 2050, all three regions were predicted to have been subject to a continuous rise in temperatures. In England, where Residence 1 was located, the annual mean temperature was shown to have a potentially small increase of 0.14 °C per decade in RCP2.6, and the rate would increase to 0.39 °C per decade in RCP8.5. In Hong Kong where Residence 2 was located, the denser population might have caused a higher projected temperature rise, that is, increasing by an additional ~ 0.15 °C in comparison with the temperatures in England. In China, the projection was more optimistic in RCP2.6, given the only 0.08 °C predicted increase per decade. With that said, rather disappointing results in RCP8.5 were revealed on the same soil, where the predicted temperature rises were 50% higher than those of the other two regions.

What is the impact of projected climate change on envelope performance?

The data recorded in the in-situ monitoring process demonstrated a correlation between temperature difference and heat flux in the selected walls. In reference to the U-value expression in Eq1, the equation can be rearranged as Eq6 below:

$$\overline{T}_{si} - \overline{T}_{so} = R_w \overline{Q}_{in} \tag{6}$$

where $R_w = \left(\frac{1}{U} - R_{si} - R_{so}\right)$ represents the thermal resistance of the wall structure.

Substituting the monitored and estimated thermal parameters with the future parameters (i.e. $\overline{T'}_{si}, \overline{T'}_{so}, \text{and} \overline{Q'}_{in}$), and assuming that the thermal resistance of the wall structure is unchanged (i.e., R_w remains the same with no future insulation retrofitting and minimal natural depreciation), Eq7 represents the same correlation of the wall at a future time:

$$\overline{T'}_{si} - \overline{T'}_{so} = R_w \overline{Q'}_{in} \tag{7}$$

Combining Eq. (6) and (7), the equation that effectively expresses the correlation between the future internal surface temperature $\overline{T'}_{si}$ and the future heat flux $\overline{Q'}_{in}$ can be formed:

$$\overline{T'}_{si} = R_w \overline{Q'}_{in} + \Delta\overline{T}_{so} + \overline{T}_{si} - R_w \overline{Q}_{in} \tag{8}$$

The in-situ monitoring campaigns collected the data of all of the parameters representing the current conditions, which were expressed in terms of R_w, $\overline{T}_{si}$, and $\overline{Q}_{in}$. Since the in-situ monitoring was conducted in the summer, the analysis focused on the cooling seasons. The estimation also assumed that the changes in the external surface temperatures, $\Delta\overline{T}_{so}$, were proportional to the projected temperature rises of the calculated regions (see the temperature gradients in Fig. 6). Based on Eq. (8), the derived equations for the three residences were as follows:

Residence 1	$\overline{T'}_{si} = 1.31\overline{Q'}_{in} + 19.89 + \Delta\overline{T}_{so}$	where $\Delta\overline{T}_{so} = 0.98\times$Projected temperature rise
Residence 2	$\overline{T'}_{si} = 0.10\overline{Q'}_{in} + 31.08 + \Delta\overline{T}_{so}$	where $\Delta\overline{T}_{so} = 0.72\times$Projected temperature rise
Residence 3	$\overline{T'}_{si} = 1.05\overline{Q'}_{in} + 28.71 + \Delta\overline{T}_{so}$	where $\Delta\overline{T}_{so} = 0.96\times$Projected temperature rise

The above equations show the linear correlations between the internal surface temperature and the heat flux at a future time. These correlations in both scenarios of RCP2.6 and RCP8.5 in 2030 and 2050 are plotted in Fig. 6.

For Residence 1, which required space heating throughout the year, it was predicted that there would be a small amount of heat loss through the wall in order to maintain a comfortable internal surface temperature at 22 °C. Under the RCP2.6 scenario in 2030, which was deemed the most moderate with respect to temperature rises, the space heating system would be required to offset the 1.50 W/m^2 heat loss from the wall. The amount of heating

Table 2
Projections to the future change of local annual mean temperature in RCP scenarios.

Residence	Projected region	Temperature change in RCP2.6 (°C)		Temperature change in RCP8.5 (°C)		Projection source
		Year 2030	Year 2050	Year 2030	Year 2050	
Residence 1	England	+0.14	+0.42	+0.39	+1.17	UKCP18 Science Overview Report [32]
Residence 2	Hong Kong	+0.30	+0.70	+0.40	+1.20	Hong Kong Observatory [33]
Residence 3	China	+0.08	+0.24	+0.62	+1.86	The third National Information Circular of the PRC on climate change [34]

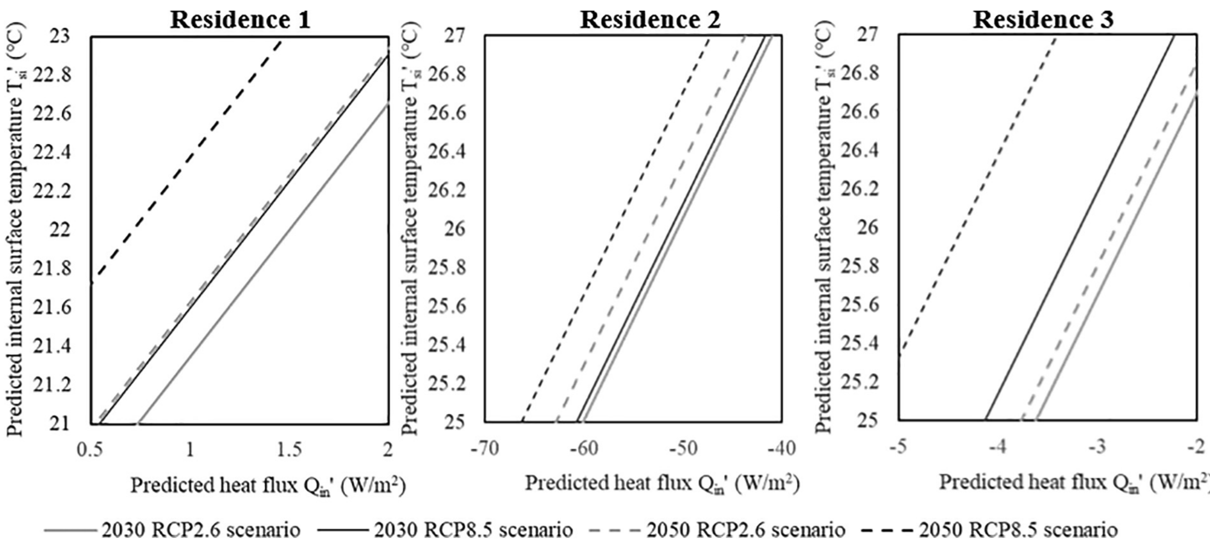

Fig. 6. Predicted relationship between internal surface temperature and heat flux in the future climate change scenarios of the three residences.

energy required to offset the heat loss would decrease to 1.30 W/m2 in the RCP8.5 scenario, which indicated that significant warming of the climate could lower the energy demand for space heating. The prediction for 2050 also demonstrates this result, where the offsetting heat flux was 1.28 W/m^2 in RCP2.6 compared with 0.71 W/m^2 in RCP8.5. In the common practice of maintaining a residential building, such small demand generally means that no additional heating is required in the space in the summer.

In Residence 2, space cooling was required in the summer season, meaning that the heat flux, the value of which would be negative, was in an opposite direction to that of Residence 1. Keeping the Tsi at 26 °C, the heat penetration rate from the outdoor environment through the wall would be 50.58 W/m^2 and 51.26 W/m^2 in the scenarios of RCP2.6 and RCP8.5 in 2030, respectively, and 53.33 W/m^2 and 56.77 W/m^2 in the respective scenarios of RCP2.6 and RCP8.5 in 2050. The overall magnitudes of the heat flux were much higher than those of Residence 1, meaning that there was an increased energy demand for space conditioning. Unlike the circumstances in Residence 1, the faster the temperature rises in the future, the more energy would be required to cool the indoor space in Residence 2. In addition, due to the low thermal resistance of the wall, the gradients of the lines were much smaller in Residence 2 than they were in the other two residences. This would bring a more significant heat flux change to the internal surface temperature. For instance, when turning down the setpoint by 1 °C, namely to 25 °C, the heat flux from outside would increase to 60.13 W/m^2, which would then raise the cooling load of the wall by 19% when all other factors were assumed to remain identical. Therefore, setting a high room temperature in the air-conditioning system would be of the greatest importance for the purpose of energy conservation in Residence 2.

In the monitoring months, Residence 3 was also in a season requiring space cooling. However, the heat flux would be much smaller for this residence than it was for Residence 2 to maintain an internal surface temperature of 26 °C. This is because the projected average outdoor temperature was lower and the ability of thermal insulation was better. The penetrating heat flux would likely be quite small in RCP2.6, which would be only 2.81 W/m^2 even after 30 years. On the contrary, the pessimistic projection of the significantly warming climate in RCP8.5 would entail that the heat flux reaches as high as 4.36 W/m^2 in 2050, which is 55% greater than that in RCP2.6. This implies that the future energy demand for space cooling will be more dependent on the actual temperature changes in Shanghai.

6. Interactive policy framework

The preceding sections have demonstrated the potential impact emanating from climate changes on the building envelope and energy demand for space conditioning, hence demonstrating the necessity of improving the current policy framework in each climatic zone. Specifically, the measured envelope features and climate impact predictions provide some policy implications on building envelopes and services. As a cross-regional study, the knowledge drawn from the three case studies can also be summarized and contrasted to enable the amelioration of future local energy-efficiency legislations that suit urban development and climate change.

6.1. Policy implications in Cambridge

In relation to the envelop performance and space conditioning demand, the current energy policy in residential buildings in the UK can be referred from the Part F and L of the Approved Documents of the Building Regulations, which cover the ventilation design and energy conservation strategies in buildings. Other voluntary codes can also be adopted to suit different sustainable needs, such as Code for Sustainable Homes, Lifetime Homes standard, and Secured by Design. Table 3 lists the current relevant regulations in Cambridge and offers future suggestions inspired by external experiences from the other two sites. These policy-related suggestions focus on improving the envelope performance and reducing energy demand for space conditioning.

Specifically, Part L of the Approved Documents sets relatively high standards for the envelope insulation (i.e. minimum U-values for each building component). The selected residence in Cambridge (Residence 1) has demonstrated good performance of its walls, and the in-situ monitoring has shown that the existing residential buildings are in compliance with the local U-value threshold. By 2050, with the projected temperature rises, the building is expected to further reduce its space heating demands. Following this trend, achieving the target of net-zero greenhouse gas emissions in the winter becomes likely. However, the current regulations focus predominantly on reducing the heat loss of individual components, lacking passive design methods such as limiting the window-to wall ratio. Such passive design could also be combined with active green power supply. In both Hong Kong and Shanghai, there are green power exchange platforms to

Table 3
Derived policy suggestions for Cambridge and potential external experiences.

	Current regulatory requirements	Future regulation suggestions	External regulation experiences
New residential buildings	• Maximum U-value thresholds of roof, wall, floor, party wall, and windows.	• Improving minimum fabric standards for the target of net-zero greenhouse gas emissions.	• Cambridge has the strictest regulation among the three cities
	• Required estimation using tabulated data by Standard Assessment Procedure (SAP)	• Restricting the maximum allowable window area.	• Shanghai: Introducing maximum window-to wall ratio to avoid excessive use of glazing fabrics
		• Restricting the solar heat gain through windows.	• Shanghai: Maximum solar heat gain coefficient to limit the heat penetration through windows.
	• Minimum efficiency for building services as regulated in Domestic Building Services Compliance Guide, including:Heating and hot water systems; Mechanical ventilation Heat pumps; Comfort cooling (simplistic EER thresholds for air-cooled and water-cooled air conditioners); Internal and external lighting.	• Improving efficiency of building services, especially for spacing cooling devices	• Hong Kong: Guidance of minimum Coefficient of Performance for most types of space cooling systems (higher type coverage than Cambridge and Shanghai). • Shanghai: Creating an energy rating system for the air-conditioning in various types and sizes, which is also linked to mandatory green certification levels.
		• Promoting low-carbon space conditioning technologies, e.g. heat pumps	• Hong Kong & Shanghai: Specific guidance on the installation of heat pumps
		• Promoting heat recovery technologies	• Shanghai: Guidance on when heat recovery is appropriate in cooling system.
		• •Requiring solar hot water in suitable dwellings	• Shanghai: Mandatory installation of solar hot water devices for low-rise residential buildings.
		• Creating incentives for on-site generations, e.g. Photovoltaic panels	• Shanghai: Financial subsidies for the capital costs of PV panels. • Hong Kong & Shanghai: Green power exchange platform.
	• Risk assessment of excessive solar gain in the summer	• Strengthening the guidelines for passive strategies to reduce the space cooling demand in the summer	• Hong Kong: Sustainable guidelines for behavioural education which is implemented by estate owners and facility management companies.
	• Target CO_2 emission rate • Dwelling Fabric Energy Efficiency	• Including more performance metrics such as annual energy consumption target and energy affordability	• Hong Kong: Systematic performance-based approach to review the overall energy consumption
Existing residential buildings	• Minimum U-value thresholds to be improved for the retained elements	• Improving minimum fabric standards for the target of net-zero greenhouse gas emissions • Promoting in-situ envelop monitoring to ensure the performance consistency from design	
	• Efficiency controlled building services for retrofitting, including:Heating and hot water systems; Mechanical ventilationInternal and external lighting	• Additional guidance on the energy retrofitting of space cooling systems • Initiating phase-out programmes to replace with higher efficiency building services	• Hong Kong: Setting standards for the thresholds of HVAC system to be applicable for Building Energy Code
	• Commissioning of the fixed building service	• Introducing requirement for periodic *retro*-commissioning campaigns • Promoting in-situ envelop monitoring to ensure the performance consistency from design	

facilitate the purchase of off-site renewable energy, reaping the overall sustainable benefit on a large scale.

Furthermore, it should be noted that the heat loss in the monitoring months was close to 0, and heat gains from the external environment are more than likely to happen in the future. This means that if the average temperature continues to increase, some overheating could potentially occur in the summer, and the current passive design might no longer be able to guarantee its control over the room temperature in the future. When the installation of domestic air-conditioning for cooling becomes a trend in the city, lacking regulations about the minimum efficiency of domestic air-conditioning products will potentially unleash an uncontrolled market in building services. For instance, residential buildings in Shanghai has an energy rating system to guide and regulate the purchase of air-conditioning. A residential building in Shanghai cannot be labelled as "green building" if it installs air-conditioning system worse than energy level II (equivalent to Coefficient of Performance (COP) = 3.40 for constant volume air conditioner with cooling capacity smaller than 4.5 kW) [35]. Energy-efficiency technologies should also be promoted for spacing cooling, such as low-carbon heat pumps and heat recovery system. A similar strategy of energy ratings may be learnt by the policymakers at Cambridge and cities that are expected to increase the demand on domestic spacing cooling.

For its large proportion of existing buildings, Cambridge has the most thought-out policy to guide sustainable retrofitting. In the Part L of the Approved Documents, both the existing envelope components and building services need to go through commissioning processes, and the poor-performing building elements are required to be upgraded to meet the guided energy-efficiency thresholds. In terms of new residential buildings, guidance for space cooling devices is suggested to be added in the regulation. For the unmet building services, phase-out schemes might also be introduced to enable constant upgrades. Future directions also include guiding the in-situ envelop monitoring to examine the actual performance and quantify energy saving opportunities as what we did to Residence 1 in this paper.

6.2. Policy implications in Hong Kong

The residential buildings in Hong Kong follow the Building Energy Code that covers the energy-efficiency practices of building envelope, lighting, air-conditioning, electrical, lift & escalator. They are all defined as prescriptive approaches with specific requirements on building services. Among those categories, the OTTV code is the first mandatory regulation introduced by Buildings Department in Hong Kong to limit the overall heat gains from the external environment. In addition, performance-based approach is also promoted to address the overall energy consumption and enable an opportunity of flexible design. Similarly, this is also a voluntary approach to suit various local conditions.

Hong Kong is a city with a very hot and humid climate, where policy and guidance on space cooling systems are relatively mature. In addition to detailed energy efficiency standards for the systems, the overall energy consumption is also controlled by covering occupancy behaviour such as encouraging higher temperature setpoints. However, residential buildings have traditionally been constructed with inadequate attention afforded to envelope performance. The selected building was constructed with relatively thin walls without insulation layers, thereby performing much worse than the other monitored buildings. The vulnerability analysis has shown an even higher importance of insulation layer in a hot climate, especially when the expected warming trend might further increase the energy demand for space cooling. The current OTTV legislation in Hong Kong is relatively easy to comply with, providing low incentives for constructing walls with a low U-value. The advantage of OTTV is clear, that is, using a single parameter to represent the overall performance. However, in building physics, this is found to be almost impossible as there are numerous interactions through a building. Many regions, such as Shanghai and Cambridge, have given up this attempt and changed back to complex tables of regulating U-values of individual building components. Hong Kong did not act that fast, possibly because natural ventilation is the key means of cooling in the summer in places where air-conditioning is not covered . Those traditional thin walls with cracks and gaps can somehow promote natural ventilation. This may be one of the reasons that Hong Kong has a resistance on changing to U-value as an indicator. The result obtained from the in-situ monitoring in this paper has proved the poorer energy performance on OTTV in an existing building compared with those in the UK and Shanghai. Therefore, strengthening the legislation with respect to envelope performance is suggested. The success of policy practices in the other two cities may be referenced, in including facilitating the compliance paths in residence developments by specifying the energy conservation parameters for each envelope component instead of having an overall loose indicator to accommodate various building envelopes. In addition to regulating the parameter representing the thermal transmittance, the access of sunlight should also be assessed, especially in the common tall residential towers in Hong Kong. In Shanghai, a simulation or calculation of the received sunshine is a mandatory procedure in the conceptual design stage for residential buildings for the sake of reducing the energy demand of space heating and artificial lighting in the winter. Similar regulatory requirements might also be applied in high-density cities like Hong Kong. Undenibly, Hong Kong has its policy highlighting the performance-based approach in the design stage as an energy compliance path, in which the annual energy consumption is used as the estimation indicator. In Cambridge, nonetheless, more dimensions of performance metrics are assessed, including the CO_2 emission rate and Dwelling Fabric Energy Efficiency. As discussed, there is room for Hong Kong to improve its policy framework of envelope performance. A Multi-dimensional energy metrics can be a useful way to help optimize the envelope design under the performance-based approach.

Similar with Cambridge, Hong Kong has detailed thresholds released for the retrofitting of existing buildings. However, in this paper, it is found that thin envelopes make some Hong Kong buildings sensitive to outdoor environment changes. Therefore, it is suggested that Hong Kong can emulate Cambridge to create policies that focus on the retrofitting of individual roofs, walls, and windows. Retro-commissioning and in-situ monitoring are also recommended to assess the potential of building energy savings to guide the retrofitting strategies. Similar with the previous section, Table 4 is developed to list the above regulation recommendations and some detailed suggestions based on the current regulation system in Hong Kong. Actionable experiences from the other two cities are also laid bare.

6.3. Policy implications in Shanghai

For the residence in Shanghai (Residence 3), the results of the in-situ monitoring show that the walls performed well, and the estimated U-value was also compliant with the local standards. There is, however, a risk associated with future energy performance. To be specific, with the expected temperature increases, the very same envelope structure will need to with stand a considerable increase in the cooling load in 2050 This implies that policymakers ought to constantly update the building standards and set stricter U-value thresholds. Given that Cambridge is closest to the net-zero energy target among the three cities, referring to the history of regulation development in Cambridge might be a simpler

Table 4
Derived policy suggestions for Hong Kong and potential external experiences.

	Current regulatory requirements	Future regulation suggestions	External regulation experiences
New residential buildings	• One minimum OTTV (RTTV) threshold for all residential buildings. • Required OTTV estimation based on tabulated material properties. • Required "Equivalent Temperature" estimation based on tabulated data.	• Indicating specific thermal resistance requirements to each building components to reduce the risk of cold bridges	• Cambridge: Strict minimum U-value thresholds all building components and requirement for high air tightness. • Cambridge: Avoiding unreliable referenced values such as Equivalent Temperature
		• •Taking the accessibility of sunshine/daylight into account, especially for dense residential towers	• Shanghai: Minimum daily time of received sunshine in the winter for each apartment.
	• Minimum efficiency for building services as regulated in Building Energy Codes, including:Lighting; Air conditioning with advanced metering and control;Electrical;Lift and escalator.	• Further setting down minimum efficiency of building services • Categorising energy ratings to set benchmarks for different energy-saving goals.	• Shanghai: Higher thresholds on the minimum Coefficient of Performance of the AC systems • Shanghai: Creating an energy rating system for the air-conditioning in various types and sizes, which is also linked to mandatory green certification levels.
		• Requiring solar hot water in suitable dwellings	• Shanghai: Mandatory installation of solar hot water devices for low-rise residential buildings.
		• Creating incentives for on-site generations, e.g. Photovoltaic panels	• Shanghai: Financial subsidies for the capital costs of PV panels. • Shanghai: Green power exchange platform.
	• Performance-based approach to give design flexibilities and trade-off allowance.	• Extending the performance criteria to CO2 emission.	• Cambridge: Using target CO2 emission rate as a performance metrics.
Existing residential buildings	No official guideline for the performance assurance of the existing envelopes	• Initiating retrofitting programmes to improve the envelope performance • Promoting in-situ envelop monitoring to ensure the performance consistency from design	• Cambridge: Minimum U-value thresholds to be improved for the retained elements
	• Efficiency controlled building services for retrofitting, including:Luminaries;HVAC systems; Lift and escalator; Electrical circuit; Or using performance-based approach	• Introducing requirement for periodic *retro*-commissioning campaigns • Promoting in-situ envelop monitoring to ensure the performance consistency from design	

way to find the direction of tightening the regulations for envelopes. According to the prediction model in this paper, the suggested U-value thresholds for exterior walls should be 12% and 30% lower than the current ones by 2030 and 2050 respectively. A Such declines should be explicitly and unequivocally reflected in the future regulation amendments.

In Shanghai, the energy performance of residential buildings is regulated in the national GB (Guo Biao) standards, which covers the minimum energy-saving requirements for envelope (U-value and daylight), HVAC systems, plumbing systems, electrical systems, and artificial lighting systems. Additionally, as the forerunner in the promotion of green building strategies in China, the Shanghai municipal government also requests all the residential buildings in Shanghai to at least meet the One Star level in the "Assessment standards for green building", significantly enhancing the energy-saving property of building complexes in the city. Therefore, Shanghai's regulatory energy efficiency thresholds are the strictest in the three cities concerned (e.g. the COP limits for air-conditioning systems are approximately 8% higher than the regulation in Hong Kong). However, compared with Cambridge's systemic guidance, the efficiency requirements for heating and hot water systems are relatively abstract and loose in Shanghai. These can well be the areas where future efforts kick in.

A prominent feature of Shanghai's energy-efficiency regulation is that it focuses on detailed prescriptive standards for building services. While this regulatory emphasis comes with the advantage of faithful implementation, the flexibility of system design is sacrificed. A variety of building technologies in Hong Kong helps the city to explore technical options to suit different needs of occupants. In Shanghai, it is also recommended to allow performance-based approaches to give trade-off opportunities to avoid unsuitable designs of building services (e.g. installing unnecessarily efficient but unaffordable systems in apartments for low-income users). Therefore, energy affordability is an important aspect in a performance evaluation and estimation. Only in this manner, can affordable, safe and practical strategies be surely adopted be in individual buildings. The essence of this idea, coincidentally, is also suggested by the Ministry of Housing, Communities and Local Government in the UK [36].

Lastly, in terms of In the existing buildings which were constructed following the previous looser envelope regulations, scheduled retrofitting guidelines are recommended. This will fill in the gap of regulatory requirements on the existing buildings in Shanghai. In line with the British Building Regulation 2010 Part L1B applied to Residence 1, thresholds of maximum U-values can also be provided for existing envelope components, and the unmet buildings are requested for envelope upgrades during retrofitting. Table 5 shows the detailed policy suggestions and the successful external experiences that could be learnt by Shanghai in a bullet-point fashion.

Table 5
Derived policy suggestions for Shanghai and potential external experiences.

	Current regulatory requirements	Future regulation suggestions	External regulation experiences
New residential buildings	• Maximum U-value thresholds for roof, wall, floor, and window (inc. skylight), based on tabulated material thermal properties. • Maximum window-to-wall ratios to avoid excessive use of glazing fabrics. • Maximum solar heat gain coefficient to limit the heat penetration through windows. • Minimum daily time of received sunshine for each apartment.	• Improving minimum fabric standards to get closer to those adopted in cool climatic zones.	• Cambridge: Setting strict envelope maximum U-values and targeting to achieve net-zero performance.
	• Performance-based overall envelope heat loss calculation to give envelope trade-off allowance.	• Extending to whole building energy efficiency targets as the performance metrics, including energy target, CO2 emission target, and energy affordability	• Cambridge: Performance-based approach to find the Target CO2 emission rate and Dwelling Fabric Energy Efficiency • Hong Kong: Systematic performance-based approach to review the overall energy consumption
	• Minimum efficiency for building services as regulated in Building Energy Codes, including: • HVAC systems; • Plumbing systems; • Electrical systems; • Artificial lighting systems.	• Improving efficiency of building services, especially for heating devices to handling potential temperature variance.	• Cambridge: Systematic energy regulation to heating and hot water systems;
	• Guidance on installation of solar energy. • Guidance on installation of ground-source heat pumps.	• Strengthening the guidelines for passive strategies in addition to active renewable energy supply	• Hong Kong: Sustainable guidelines for behavioural education which is implemented by estate owners and facility management companies.
Existing residential buildings	• No official guideline for existing buildings apart from voluntary green building certifications	• Initiating retrofitting programmes to improve the envelope performance • Initiating phase-out programmes to replace with higher efficiency building services • Introducing requirement for periodic *retro*-commissioning campaigns • Promoting in-situ envelop monitoring to ensure the performance consistency from design	• Cambridge: Minimum U-value thresholds to be improved for the retained elements

6.4. Policy interactions in the cool, warm and hot climatic zones

The policy suggestions for the individual cities can be further extended to a more general policy framework to be referenced by other cities and countries in the cool, warm and hot climatic zones. Fig. 7 uses a diagram to briefly showcase the suggestive policy framework based the interactive policy analysis from the previous discussions. The suggested strategies focus mainly on the direct high-performance building envelope guidelines and the indirect energy demand reduction through the HVAC systems. Each strategy is tagged with the most suitable building stage (new or existing) and the policy source of the city to enable the best practice. There is no denying that lighting and electrical systems can also generate internal heat gains in the building; yettheir thermal impacts on the energy consumption is much smaller compared with building envelope and space conditioning systems. We therefore did not heed them in this paper.

From Fig. 7, it can be seen that the compliant building could go along two paths: the performance-based and prescriptive approaches. The former one gives certain design flexibility, but the minimum energy requirements for each building element should be complied. Three metrics are suggested as the compliance criteria, including energy target, CO_2 emission target, and energy affordability. Any unmet criteria would need to go back for re-design or retrofitting until the performance passes muster with the regulation. For building envelope regulations in the prescriptive approach, Cambridge contributes the most advanced experiences for both new and existing buildings. The possible takeaways may include strict U-values, commissioning requirement, and passive design. As a city that mainly adopts the prescriptive approach, Shanghai added detailed suggestions on other envelope parameters and options for trade-off analyses. Finally, since in-situ monitoring has proven to give more accurate energy-saving directions, this practice is also advised for existing buildings in energy diagnosis and performance verification stages. In all the three residences investigated in this paper, the root causes of the performance gap between design and operation are not clear. However, many studies have found that up to 30% of performance differences are owing to construction quality and structure deteriorations. Adopting in-situ monitoring in the performance assessment phase can effectively reduce this risk by probing the real operation status.

In terms of building services, the regulation of HVAC system is strictest in Shanghai. Because of the mandatory compliance decree of green building certificates, regulatory energy ratings are given to various building services and on-site renewable energy generation is requested for low-rise residential buildings. It is noted that the three cities have relatively detailed regulations for the HVAC systems that are often times used in local buildings. However, as discussed, the climate change potentially creates new demand for HVAC systems in different regions. More comprehensive regulations covering all types of systems are thus warranted. At the operation stage, Hong Kong has some experience on guidance occupancy behaviour and minimum system efficiency thresholds for retrofitting. Akin to quality control in envelope, it is also sug-

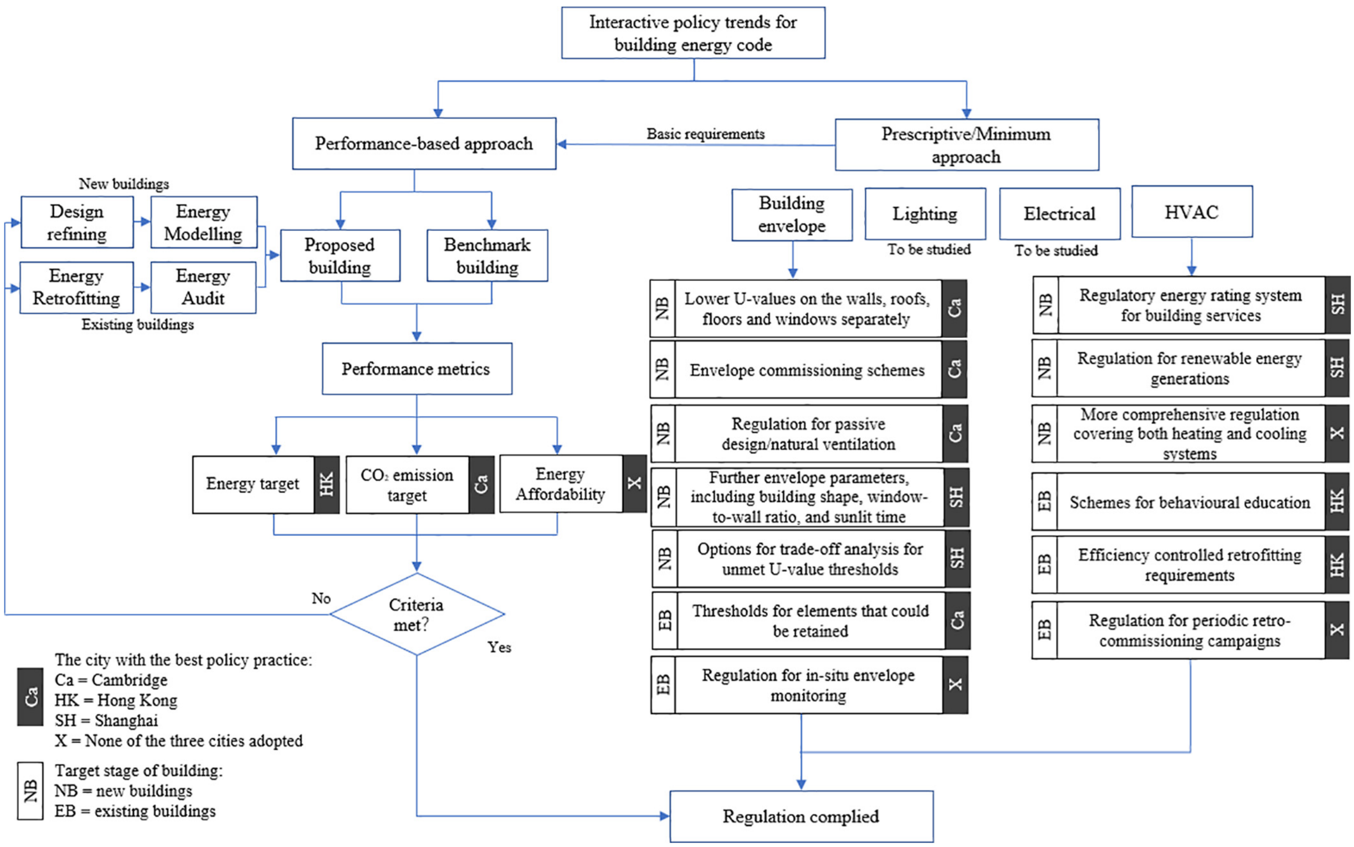

Fig. 7. Suggested general policy framework combining the best practices from the three cities.

gested that periodic *retro*-commissioning campaigns must be launched for the existing building services to ensure faithful operations as per designed.

7. Conclusions

In his seminal book, Majumdar (2002, p. 1) laments that buildings "contribute to a serious environmental problem because of excessive consumption of energy and other natural resources". That said, as he subsequently elaborates, we should not lose heart primarily because buildings, in light of advances in technology and evaluative capabilities, "can [also] be designed to meet the occupants' need for thermal and visual comfort at reduced levels of energy and resources consumption [37]. Thermal transmittance, widely known as the U-value of a building envelope, is a key indicator that assesses the energy performance of buildings. Therefore, it is regulated by policies in many countries and regions. By conducting in-situ monitoring campaigns in residences of three regions with varied climate zones, we found empirical evidence of variations in wall performance of residential buildings during the post-occupancy stage. Compared with the method of tabulated estimation, in-situ monitoring has demonstrated its advantage of higher precision in gauging the levels of energy efficiency of the operating buildings.

Specifically, this paper reveals that climate itself can elicit significant impacts on the actual energy saving performance of buildings. Coordinated policy collaborations and information exchange among regions under different climatic conditions are therefore needed to strengthen the resilience of residential buildings against the potential risks associated with climate change or demand growth. For instance, our results show that the residences in Hong Kong are more vulnerable to temperature changes due to loose regulations on building envelope insulation. Government officials in Hong Kong can probably take a page from the book of the United Kingdom where the initiative of net-zero building envelopes is being resolutely implemented. In addition, by virtue of the in-situ monitoring campaigns, this article highlights the effectiveness of different energy efficiency policies on the energy performance of individual buildings located in different climate zones. This pioneering cross-regional analysis hence carries rich policy implications – that is, instead of taking one-size-fits-all measures on elevating the energy efficiency of operating buildings, more context-contingent, climate-sensitive, and idiosyncratic energy-efficiency standards and regulations merit exploring and experimenting.

Irrefutably, this paper is not immune to limitations. A limited sample size (i.e., one case study per climatic zone, totalling three cases) affords us no more than a glimpse into the climatic contingencies of the interplay between buildings' energy-saving capacity and their envelope performance. Following in our footsteps, future studies ought to be conducted on a wider range of buildings so that biases arising from the selection of building types can be effectively eliminated. In sum, our study points out a clear direction and leaves fertile ground for like-minded scholars to design and tailor energy-saving standards that best suit the building stock in their respective communities and ultimately advance the local interest in the long haul.

CRediT authorship contribution statement

Weili Sheng: Data curation, Methodology, Software, Writing - original draft. **Bo Wen:** Issue Framing, Investigation, Writing-Revising, and Editing. **Lin Zhang:** Conceptualization, Methodology, Investigation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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