

# Developing a design framework to facilitate adaptive behaviours

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# Developing a Design Framework to Facilitate Adaptive Behaviours

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## Abstract:

Adaptive behaviour has a significant impact on the quality of indoor environment, comfort, and energy consumption. Therefore, facilitating positive occupant behaviours will improve these three factors. The aim of this paper is to develop a design framework that can be used as part of the design process to facilitate adaptive behaviours.

This paper reviews studies that focus on reasons behind adaptive behaviours, and implication of these adaptive behaviours on the built environment. This paper highlights that 'Context', 'Occupant', and 'Building' (COB) have the most influence on adaptive behaviours. However, in most cases their influence is not considered holistically. This study also illustrates that adaptive behaviour has implications for the quality of Indoor environment, level of Comfort, and Energy consumption (ICE). This paper introduces a framework consisting of three stages: 1) Evaluate the relation between COB and ICE factors with adaptive behaviours holistically; 2) Design building's controls for 'environmental behaviours', set-up strategies for 'personal behaviours', and find a balance between these two; 3) Monitor the performance of adaptive behaviours through Post Occupancy Evaluation (POE).

**Key Words:** Adaptive Behaviours; Built Environment; Overall Comfort; Energy; Framework

## Highlights:

- To design building's controls and setup strategies for personal behaviours, factors related to behaviours are studied.
- Adaptive behaviours can create balance between indoor quality, comfort and energy use (ICE factors).
- A design framework is proposed to facilitate environmental and personal adaptive behaviours.

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## 1. Introduction

Occupants usually respond to discomfort in two regulative ways: by adapting their environment (environmental adaptive behaviour) or adapting themselves (personal adaptive behaviour) [1]–[5]. Many studies have referred to the role of adaptive behaviour on improving the occupant's state of comfort and quality of environment [4]–[11], and its effect on the occupant's forgiveness and satisfaction [12]–[19]. Occupants who can control their environment suffer from fewer building related symptoms [20]–[22] and report lower degrees of discomfort [9]. Occupant behaviour is a major source of building performance uncertainty [23]–[25] and is the main reason for the gap between predicted and measured energy performance of the building [24], [26]–[29].

Limited understanding of occupants' behaviours in buildings results in increased energy consumption, poor indoor quality and discomfort. The relationship between comfort and adaptive behaviours is quite complex, mainly because factors affecting one aspect of comfort also impact on other aspects [30], [31]. For example, opening or closing curtains affects both visual and thermal comfort, possibly in an opposing way. State of comfort and energy consumption can also conflict with each other. Occupants' comfort can affect energy demand significantly [31]; for example, the study by Dubrul (1988) suggests that while ventilation rate in housing needs to be minimized to save energy, an adequate supply of ventilation is required to maintain comfortable and healthy conditions for the inhabitants and to avoid damage to the building fabric from pollutants like moisture [32]. It is important to find a balance between different aspects of comfort [33], indoor environment and energy consumption in order to have efficient and comfortable buildings. This balance can be achieved by taking appropriate adaptive behaviours, therefore, it is important to provide opportunities for facilitating and practising adaptive behaviours in buildings. The main contribution of this paper is to develop a design framework that is recommended to be considered as a part of design process to facilitate adaptive behaviours. The results can be used by building designers to design and retrofit buildings that better account for occupant comfort, can provide quality of indoor environment and save energy.

## 2. Methodology

To develop a design framework to facilitate adaptive behaviours, it is necessary to study factors that affect adaptive behaviours and factors that are affected by adaptive behaviours. For this reason, the inclusion criteria for selecting materials to review are studies that focus on the reasons for occurring or not occurring adaptive behaviours (Group A studies) and studies that examine the implications of adaptive behaviour on the built environment (Group B studies). Group A studies look at situations in which adaptive behaviours happen, change in frequency and time, or how behaviours are restricted or facilitated. Group B studies highlight the direct consequence of adaptive behaviour as it can change occupants' perception of behaviour. As a result, 150 studies are selected for more than four decades (1973 to 2018), from 23 countries (Figure 1) based on their connection to group A or group B studies.

This paper critically reviews group A and B studies with the aim of developing a framework that can be used by building designers to facilitate adaptive behaviours and improve the quality of built environment.

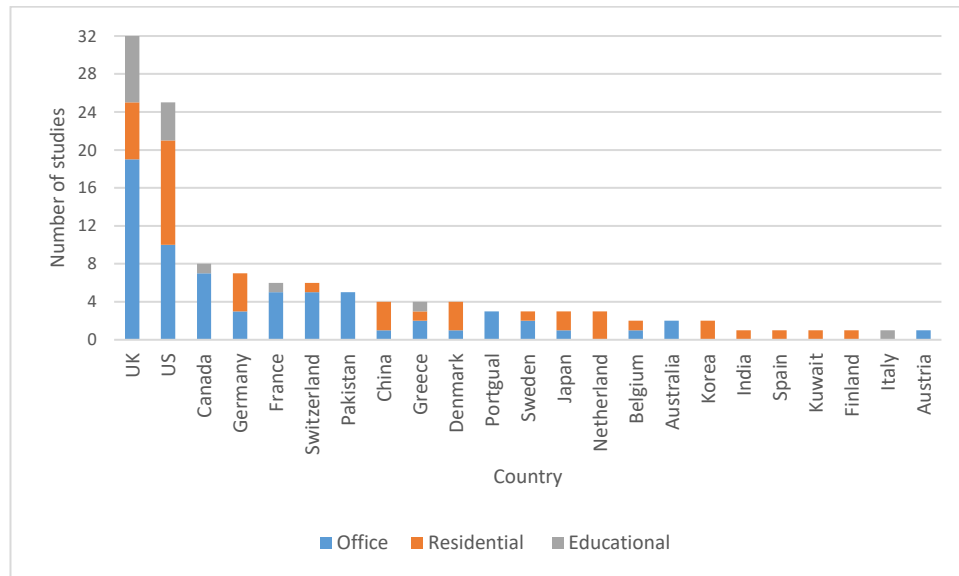


Fig 1. The number of studies in each country based on different building use

Reviewing group A studies categorizes all the factors that affect adaptive behaviours into three main groups: Contextual, Occupant and Building related (COB). Contextual factors include climatic factors, such as ‘temperature and seasonal changes’ and ‘sun effects and its direction’, and urban factors, such as background noise level, pollution level, and outside views. Building related factors include type and design of spaces and controls, and interior layouts. Occupant related factors are related to the occupant’s individual characteristics (i.e. psychological, physiological, economic and social background) and their occupancy patterns in the building. Reviewing group B studies reveals how the occupant’s behaviour impacts on the Built Environment by changing the Indoor quality, Comfort perceived by occupants, and Energy consumption (ICE factors). Figure 2 shows a research taxonomy of structure and logical flow for the paper.

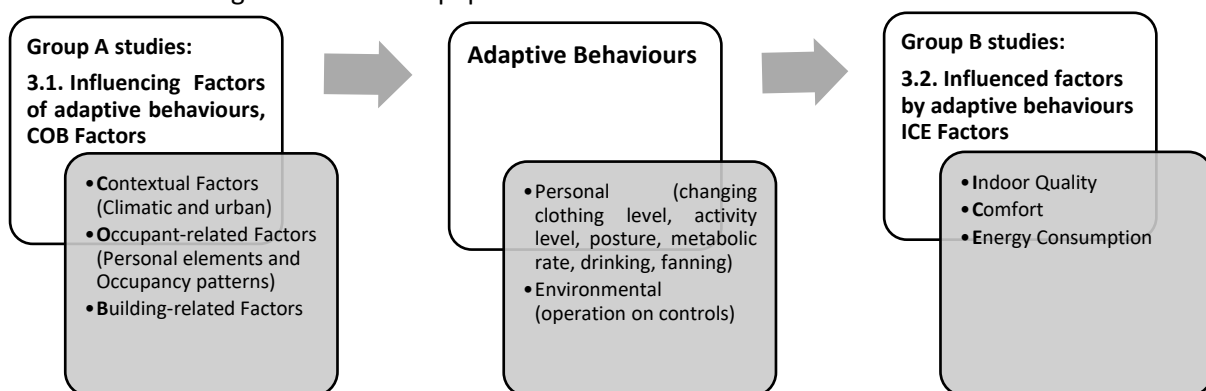


Fig 2 Research taxonomy of structure and logical flow for the paper.

This paper reveals the most important and most recurring factors affecting adaptive behaviours and also the factors that are influenced by adaptive behaviours. The outcome of this study is to help building designers maximize occupant’s interaction with building’s controls and also facilitate strategies for beneficial personal behaviours.

### 3. Adaptive Behaviours

#### 3.1. Adaptive Behaviours and Influential Factors in Various Buildings

The first part of the paper considers factors that impact on both environmental and personal adaptive behaviours in office, residential and educational buildings.

##### 3.1.1. Office Buildings

- Environmental Behaviours

Environmental adaptive behaviours, including the operation of windows and shades, have a direct consequence on energy consumption. Windows and shades are among the controls that can easily and quickly change environmental conditions and are closely connected to thermal comfort, visual comfort [34]–[37], indoor air quality, acoustic comfort [37], privacy [38]–[41] and outside views [42]. Studies show that window operation is related to contextual factors, such as temperature and seasonal changes [2], [8]–[10], [43]–[57], building-related factors, such as previous state of windows [44], [52], [54], window size [10], [43], distance to windows [9], and occupancy patterns [10], [45], [48], [54], [57].

The operation of shades is also correlated with COB factors. Firstly, contextual factors such as ‘sun effects’ [50]–[71], ‘temperature changes’ [52], [60], [63], [68], [70], [73] and also outside views affect shade operation. There is an evidence that, when there is a pleasant view to the outside, shades are closed less frequently as occupants like to enjoy the outside view [58], [39], [65], [38], [71], [77], [41]. Blinds, as one the shading devices, are usually closed to avoid direct sunlight and glare [39], [38], [69]–[71]. Sun effects influence the Mean Shade Occlusion (MSO)<sup>1</sup> in each orientation; in northern hemisphere, higher MSO is observed on south facing façade [58]–[60], [39], [61]–[63], [40], [64], lower MSO on north façade [58], [59], [39], [61]–[63], [40], [64], [74] and intermediate results for east or west facades [59], [63], [40], [74]. The frequency of shade adjustment is higher on south [64], [65], [72] and west facades [72], [75], and is lower on north and east facades [72]. Several studies suggest that the ratio of south MSO to north MSO is between 1.4 and 2.6 [58], [39], [61], [40], [64], [76]. Secondly, shade operation is affected by building related factors such as type of office, interior layout and type of blind. More operation is observed in single occupancy offices than in double-occupancy and open plan offices [64], [71], [78], which is due to having higher level of control over shades. Shades are opened more when occupants are sitting near the windows [9]. Type of blind affects rate of blinds’ operation [38], [70], [79]; automated, remotely controlled and motorized blinds show a higher operation rate than manual ones. Thirdly, shade operation is correlated with occupancy patterns (arrival and departure) and occupant’s individual characteristics. Psychologically, occupant’s behaviour on the operation of blinds is affected by long term perception of the environment rather than by short term dynamics [58], [63], [65], [67], [69], [72]; e.g., the state of blinds remains usually unchanged for weeks or months [58], [70], [80]–[82]. Behaviour is also affected by the need for privacy in the workplace [39], [40], [38], [41]. Physiologically, blind adjustment is predicted by occupants’ brightness sensitivity [61]; and socially, blind operation is influenced by trying not to upset colleagues in the workplace [60]. Blind operation is also correlated with the occupant’s pattern of arrival and departure, with more operation upon entry or at the end of the work day [39], [65], [69], [83].

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<sup>1</sup> Mean Shade Occlusion (MSO)<sup>1</sup> in each orientation is defined as the average fraction that shades are closed for some group of windows [67].

Occupants operate artificial light to satisfy their visual needs and comfort [84]. Bordass (1995) suggests that limited understanding of occupant behaviour is one of the reasons for uncontrolled levels of lighting in many open-planned offices, even with automatic controls [78]. Studies have shown that operation of lights is correlated with illuminance level and work plane illuminance [66], [38], [77], [85]–[89], type of office (open-plan or individual) [78], [90], access and proximity to controls [75], [87], [90], control's ease of use [91], occupant's physiological elements (e.g. mood, eyestrain and metabolic rate) [86] and occupancy patterns [59], [66], [38], [81], [85], [87], [88], [90], [92]–[94]. Lights are switched on when occupants enter offices [59], [38], [81], [85], [87], [88], [90], [92]–[94] and are usually switched off when they leave or are absent for a long time [59], [66], [85], [87], [88]. Intermediate 'switching on' usually occurs at lower illuminance [62], [92], [95] or at clearly uncomfortable situations, indicating that switching is usually not an intermediate event [87].

Research on doors, fans and HVAC is not as comprehensive as that on other controls such as windows, shades and lights. Studies illustrate that door operation is connected to indoor temperature [52], [53], occupancy patterns and working hours [57], internal noise level [23]. Fan operation is correlated with temperature changes [9], [45], [52], [53], [96]–[98], and frequency of heater use is correlated with temperature [2], [96] and type of heating system [99].

- Personal Behaviours:

Studies on personal behaviours that make the occupant more comfortable by changing metabolic rate or internal heat are not developed compared to studies on environmental behaviours. Studies highlight that clothing level depends on the variation of temperature [20], [45], [52], [96], [100]–[104]. Drink consumption is also correlated to temperature and seasonal changes [52], [101]. However, activity level is either negatively correlated to indoor temperature [105] or not correlated to indoor temperature [103]. COB factors affecting adaptive behaviours and controls in office buildings are presented in Table 1.

Table 1. Factors affecting adaptive behaviours and controls in office buildings

Group		Study	Country	Outcome of the Study	How outcome can facilitate adaptive behaviours		
Window operation	C	[43]	UK	Window operation is related with $T_{out}$ (76%), solar gain (8%) and wind speed (4%).	Window's size and number of openings should be designed by considering changes in seasons and outdoor variables (i.e. temperature, solar gain, wind), especially when variables fluctuate significantly during day and night or during different seasons. For example, the operation of windows is less frequent during winter compared to summer, however designing small openings alongside larger openings can provide natural ventilation without significant loss of heat and energy. Window operation will not be limited by factors such as rain, snow, wind and security concerns if window is efficiently and properly designed.		
		[49]	China	Few window openings occur when the outdoor temperature is less than 10°C -15°C, but the percentage increases when the temperature is between 15°C-30°C and is at maximum when temperature is between 25°C-30°C.			
		[9], [46]	UK	Window control is affected by $T_{in}$ in summer and by $T_{in/out}$ in winter.			
		[51]	UK	Opening windows is influenced by indoor temperature while how long it stays open is influenced by outdoor temperature.			
		[106]	Pakistan	Window opening increases when indoor temperature is above 20°C in Switzerland and UK [9], [56] and when is above 16°C in US [45].			
		[9], [45], [56]		The percentage of window opening area is the highest in summer, the lowest in winter and is in between in spring and autumn, with the highest frequency of window operation in spring and autumn and the lowest frequency of window operation in summer.			
		[8], [46]	UK				
		[10]	Germany				
	B	[10]	Germany	Small clerestory windows are opened less frequently, remained open for a longer time and are usually used for night ventilation, however large windows are opened more frequently for a shorter time and are mostly closed during the night.	Windows in different designs and sizes can provide different aspects of comfort (thermal comfort and indoor air quality) and can be kept open/closed for a shorter/longer period. Workstations should provide occupant's easy access to windows, without locating them in sun patches.		
		[43]	UK	Small windows are usually opened to provide indoor air quality while opening large windows is strongly influenced by outdoor temperature.			
		[9]	UK	Window operations are mostly done by occupants sitting near windows (interior layout).			
		O	[9]	UK		Window open is closely connected with thermal sensation of occupants.	Understanding occupants' thermal sensation (based on age group and activity) and occupancy patterns to design an environment that is positively perceived by them, facilitates their efficient window operation.
			[55]	Cambridge, UK		Windows are used often by occupants with high perceived control and positive cognition over environment than with low perceived control.	
			[10]	Germany		Windows are more manipulated in the morning, at lunchtime and then in the evening, according to their occupancy schedule.	
Shade operation	C	[65]	UK	30% of the blind occlusion is explained by the amount of sunshine on the façades.	Occupants' type of activity and amount of daylight they need during their occupancy schedule help to decide over the best orientation for their shared space. Careful attention should be paid to the site in which buildings are constructed to provide occupants pleasant outside views and visual comfort. Outside views encourage occupant's efficient operation on blinds.		
		[64]	Canada	Shade movement rate is reported 5 times higher for south facing façade than for north facing façade (sun effects).			
		[71]	Switzerland	Upper blinds are lowered four times more compared to the other blinds as they do not obstruct occupant's view when lowered.			
		[77]	Denmark	Blinds are left more open to have outside views although occupants would have been more comfortable if they had pulled down to control solar radiation.			
	B	[64], [78]	UK, Canada	Blinds are less frequently operated in open-plan office compared to individual office because it limits controls' adjustment and makes occupants more inactive.	If designing individual or cellular office is not possible, number of occupants sharing an open-plan office should		

		[9]	UK	Blind adjustment is more frequent when occupants are sitting near the windows.	be reduced to have more active occupants. Similarly, if locating blinds close to workstations is not possible, remotely controlled blinds can be designed.
		[70]	France	In similar context, remotely controlled blinds are used three times more than manually controlled blinds.	
Light Operation	B	[78]	UK	Lights are often left on in an open-plan office that limits operation of controls compared to an individual office.	The location and friendly-design of the lighting controls affect frequent and efficient operation of lighting systems because they will be operated when light level is low rather than switching lights on upon arrival and then switching them off on departure. Furthermore, local controls can satisfy visual needs of higher number of occupants.
		[90]	Salford, UK	Lights' switches closer to occupants are turned on more frequently.	
		[75]	US	Having access to light dimmers on occupant's desk results in more dimming adjustment.	
		[91]	UK	Where lighting controls are not easy to use, occupants choose lighting levels that reduce the need for frequent operation.	
		[87]	Switzerland	Lights are switched on and off upon arrival/departure as lights are placed close to the door rather than close to occupants' workplace.	
	O	[86]	France	12% of the subjects change electric lighting according to their type of activity.	Number of occupants sharing an open-plan office should be reduced with a good understanding of their activity type to provide them higher levels of control.
		[90]	Salford, UK	Light switch frequency reduces due to high number of occupants in an open office due to social aspect of trying not to upset colleagues.	
Fan/HVAC	C	[96]	Pakistan	Proportion using fans and heaters is correlated with $T_{in}$ ( $R^2 \cong 0.75$ ) and $T_{out}$ ( $R^2 \cong 0.8$ ).	The operation of fans/AC/heating systems is mostly related to climatic conditions in office buildings. However, occupants are less concerned about system's energy use compared to residents, which suggests designing more energy efficient cooling or heating systems in offices.
		[2]	6 countries <sup>2</sup>	AC application for cooling starts at $T_{out} > 25^\circ\text{C}$ and for heating stops when $T_{out} > 15^\circ\text{C}$ .	
		[45], [52]		More fans are on when $T_{in} > 26^\circ\text{C}$ in Canada, USA [45] and when $T_{in}$ is $20\text{--}25^\circ\text{C}$ in Switzerland [52].	
		[97], [98]	6 countries <sup>3</sup>	Fans are used when $T_{out} > 20^\circ\text{C}$ , and their use is at Max when $T_{out} > 30^\circ\text{C}$ .	
Personal Behaviours	C	[96]	Pakistan	Clothing worn is correlated with both $T_{in/out}$ ( $R^2 \cong 0.65$ ), but it remains constant outside the interval $20^\circ\text{C}$ – $30^\circ\text{C}$ as occupants reach limits of acceptable clothing in offices.	The correlation between temperature and clothing level shows how occupants adjust themselves to reach comfort. Therefore, giving occupants the freedom to choose their clothing level without imposing strict uniform policies helps reaching higher levels of comfort without using excessive energy. Similarly, having frequent short breaks in between working hours to change metabolic rate and activity level can help achieving more comfort.
		[100]	UK	Mean Clo values decrease from 0.8Clo to 0.66Clo as mean external temperature increases from $6.7^\circ\text{C}$ to $27.3^\circ\text{C}$ .	
		[102]	Australia, Canada, US	Clothing insulation is correlated with $T_{out}$ ( $r=0.45$ ), $T_{op}$ ( $r=0.3$ ), $H_r$ ( $r=0.26$ ), and has very insignificant correlation with air velocity ( $r=0.14$ ) and metabolic activity ( $r=0.12$ ).	
		[45]	Alameda, CA	Clothing level changes from 0.5–0.6 Clo in the summer to 0.7–0.8 Clo in the winter which is best explained by running mean outdoor temperature.	
	O	[105]	Australia	Activity level is negatively correlated to indoor temperature as occupants purposely reduce activities as temperature raises.	

<sup>2</sup> UK, Pakistan, Sweden, France, Greece Portugal



### 3.1.2. Residential Buildings

Researches on occupants' adaptive behaviours in residential buildings are mainly focused on window operation, and then on Air Conditioning (AC) and heating systems. The operation of shades and lighting controls, and personal behaviours are not treated comprehensively, however, their effect on comfort and energy saving is significant. Contextually, studies have shown that window operation is affected by temperature and seasonal changes [32], [107]–[119], CO<sub>2</sub> level [3], [4], [114], [117], [120], wind speed [32], [110], [111], relative humidity [108], [111], [113], [114], solar radiation [32], [112], precipitation levels [32], and background noise level [32], [112], [121]. Building related factors that affect window operation include type of dwelling [32], [111], room type [32], [108], [110], floor area [112], window size and design [32], [107] and security [32], [121], [122]. Occupant related factors that affect window operation are residents' energy saving concerns [32], [121], [122], number of residents [3], [108], [111], resident's activity and lifestyle [32], [108], [111], [114], [115], [122] and occupancy patterns [32], [111].

Fans and doors are usually operated to provide cross ventilation and to increase air movement [119]. AC operation is correlated with temperature changes [123]–[129], occupancy patterns and activities [124], [126], residents' health concerns [130] and their energy saving concerns [5]. The operation of heating systems and thermostats in households is correlated with outdoor and indoor temperature [112], [117], [125], [129], [131], poor thermal integrity [132], room and house type [133], [134], type of heating systems and thermostat [112], [135]–[138], resident's age [99], [139]–[143], and energy saving concerns [133]. Door operation is also found to be correlated with temperature and seasonal changes [109], [116]. COB factors affecting adaptive behaviours and controls in residential buildings are presented in Table 2.

### 3.1.3. Educational Buildings

Adaptive behaviour in educational buildings is important because it affects student's state of comfort [144] and consequently health and performance [145]–[147]. There are fewer studies in educational buildings compared to office and residential buildings. Generally, less adaptive behaviours are taken during teaching activities than during breaks as pupils are concentrated on lessons [34], [148]. Window operation is influenced by indoor and outdoor temperature [4], [34], [144], [148], [149], CO<sub>2</sub> level [149], humidity [119], [149], noise level [37] and security [150] in educational buildings. Blinds are adjusted to control glare or sunlight [151], [152], prevent overheating [152], limit outside distractions [152], provide outside views [153] and to darken the room for presentations [151]. Window and doors are operated more when temperature is high [4], [149] rather than when indoor air quality is low [154], because air quality is not perceived as temperature due to gradual sensory fatigue or adaptation [155]. Blind's ease of use [153], [156] and window design [153] also affect the operation of blinds. Use of heaters is affected by interior layout; the air flow through the heater battery is reduced to decrease discomfort to the students sitting near the trench [150]. Studying personal behaviours in primary schools in UK shows that the time personal behaviours happens is more related to occupancy patterns and type of activity, but the frequency of personal behaviours is more related to season and outdoor temperature [144]. Students' clothing level usually follows running mean temperature, sequence of temperature and long term fluctuation in temperature [157]–[159]. COB factors affecting adaptive behaviours and controls in educational buildings are presented in Table 3.

Table 2. Factors affecting adaptive behaviours and controls in **residential** buildings

Group		Study	Country	Outcome of the Study	How facilitating adaptive behaviours
Windows	C	[108]	Wales, UK	Window opening is related to humidity in winter and to mean daily temperature in summer.	Apart from environmental variables, type of room (bedroom, living room or kitchen), security and energy saving concerns of residents should be considered for deciding over window's size, design and opening to facilitate residents' efficient window operation. Factors affecting window operation in residential buildings are more varied than those in office buildings because of residents' more varied occupancy patterns, age range, personal adaptive behaviours, household activities, number of residents in a house, their energy saving and security concerns.
		[32]	5 countries <sup>3</sup>	Windows are operated more at higher temperatures, higher solar radiation, lower precipitation levels and lower wind velocities.	
		[109], [113], [115]	CN, US, KR	Windows are opened more often and stay open longer in summer than in winter ( $T_{out}$ ).	
	B	[32]	5 countries <sup>4</sup>	Windows in bedrooms are left open for longer periods and the percentage never opened is higher in living rooms. Window design, its frame and how it opens, affects window opening behaviour.	
		[32], [108], [110]	5 countries <sup>4</sup>	Window opening is more common in bedrooms that are the buildings' main ventilation zones.	
		[160]	Denmark	Smaller windows are used seldom.	
	O	[32], [121], [122]	5 countries <sup>4</sup> , US	Windows are kept closed mainly due to security and energy saving concerns.	
		[32], [108], [111], [114], [115], [122]	5 countries <sup>4</sup> , Korea, US	Windows are operated more in dwellings with smoking behaviour, with more house-keeping, cooking, showering activities and in dwellings that are occupied longer.	
		[3], [108], [111]	UK, US, DE	Windows are operated more in households with larger families.	
		[32]	5 countries <sup>4</sup>	Window opening is maximum in the morning, stays high in afternoon and decreases gradually until 5 p.m. when another peak happens due to return of work and decreases again during evening.	
AC	C	[123]–[126]	CN, KR, JP	The probability to switch on AC increases when $T_{in}$ overcomes 25–30°C.	Type of room, type of AC and heating systems, residents' activity and their age range affects temperature set for cooling and heating systems.
	O	[124], [126]	China, Japan	Turning on AC is frequent before eating and sleeping but tuning it off is more frequent after getting up and when leaving the room.	
		[130]	Japan	AC is not used by half of the respondents due to its harmful effects on health.	
Heating/Thermostats	C	[131]	China	Heating systems are more frequently on when indoor temperature is between 10–14°C.	To provide thermal integrity, the location of these systems should be carefully designed. To save energy and to respond to needs of all residents, energy efficient heating/cooling systems alongside with other controls such as windows should be designed.
		[134]	US	Different temperatures are chosen for different parts of the houses, with living rooms being about 2°C higher than bedrooms.	
		[132]	US	Thermostats are manipulated frequently due to poor thermal integrity to keep $T_{in}$ more tolerable.	
	B	[136]–[138]	US, UK	Programmable thermostats compared to manual thermostats are less likely to be kept at a constant temperature, with programmable thermostats having higher settings.	
	O	[99]	Netherland	Heating systems are on for more hours and ventilation systems are on for less hours in presence of elderly people and children.	
		[139]–[143]	NL, CN, UK	Higher temperature settings are preferred by older people.	
		[133]	Sweden	Residents in detached houses adopt to lower $T_{in}$ than those in apartments to save energy.	

<sup>3</sup> Belgium, Germany, Switzerland, Netherland, UK

Table 3. Factors affecting adaptive behaviours and controls in **educational** buildings

B	F	Study	Country	Outcome of the Study	How facilitating adaptive behaviours
Windows	C	[149]	Primary schools, UK	Window operation and window intervention (changing window state) is influenced by $T_{out}$ , $H_r$ , fresh air and $CO_2$ level. Window closing is influenced by cold draughts and $T_{in}$ .	Apart from environmental variables, background noise level and security concerns can restrict adaptive behaviours on windows. Appropriate site selection (avoiding noisy areas) and secure operable windows that are designed based on height of children can facilitate adaptive behaviours on windows.
		[34], [148]	IT, GR	Window opening and closing can best be predicted by Indoor temperature.	
		[37]	Primary schools, UK	Windows are closed by teachers and pupils in noisy areas to reduce the effect of noise especially during quiet activities, resulting in overheating and poor air quality.	
	B	[150]	Secondary schools/UK	Automatic windows in classroom located on the ground floor are shut due to security reasons and classrooms rely on mechanical ventilations to provide sufficient ventilation.	
Shades	C	[151]	USA	Closing blinds is mainly for controlling sunlight (92%) in south facing classrooms and for darkening the classroom for media presentation (81%) in north facing classrooms.	To increase the operation of windows and blinds, dividing windows by light shelves is a good design solution to provide thermal and visual comfort, reduce glare, increase daylight level and provide outside views. Dividing windows into two can also increase natural ventilation. To facilitate efficient operation of blinds, the best orientation for classroom activities and its effect on size and design of windows should be considered. Blinds should be easy to access and use for its frequent operation as it can save lighting energy, reduce glare and provide outside views.
		[152]	UK	Blinds are closed to reduce glare, prevent overheating and limit outside distractions.	
	B	[156]	New York, USA	31% of the teachers never operate their blinds, 21% adjust them monthly, 18% adjust on a weekly basis, 17% daily and 13% selected other. Not operating blinds is because blinds are difficult to use or broken after years of use.	
		[153]	Studio/US	The major factor for not operating blinds is their hard operation.	
		[153]	Open-plan studio/US	Blinds are closed less by occupants whose workstations are located within the light shelf zone than those who are in the area with conventional windows. Occupants raise shades more often when they are given full control over the view part of subdivided windows.	
Lights	C	[88]	USA	In intermittently spaces like schools switching activity occurs throughout the day, with a decline in use of artificial light as daylight level increases. The probability of switching on artificial light is correlated to minimum working plane illuminance; illuminance levels less than 100 lx lead to significant increase of the switch on probability.	To promote intermittent light switching in schools, blinds should be accessible and easy to use to provide as much natural light as possible in the classroom and to block unwanted sunlight and heat.
Personal Behaviours	C	[157]	England, UK	Children's clothing and their behaviour usually follows running mean temperature or the sequence of temperatures than actual temperature.	Students should be given the freedom to take personal behaviours, such as drinking or changing the combination of their school uniform (socks/tights, skirts/trousers, trousers/shorts, with or without jumper/cardigan). It is important that students, especially primary and secondary school children, be advised and reminded on personal behaviours, because they sometimes do not think of it or forget it. When temperature causes discomfort, type of activity in the classroom can be changed shortly to provide higher levels of comfort.
		[158]	UK	Clothing changes little with short term variation of temperature but more with long term fluctuation in temperature. Clothing weight depends on the room temperature; optimum temperature for students with winter clothing occurs at 18.5°C, for students with heavy clothing occurs at 21.5°C and for students with light clothing occurs at 24.5°C.	
		[159]	five local primary schools/UK	The number of clothes follows long-term trend of temperature and there is a little change in clothes during the day as students do not think of changing or cannot make any adjustment to the combination.	
	O	[161]	UK	Open activities are preferred within activities' limitation as temperature increases more.	

#### 3.1.4. Results

The summary of review over Contextual, Occupant and Building related (COB) factors influencing environmental and personal behaviours in different building types is highlighted, and areas that need further development for future studies are discussed.

- To facilitate adaptive behaviours, COB factors should be studied holistically for designing building's controls or setting up strategies for personal behaviours. Firstly, contextual factors need to be considered to avoid scenarios in which adaptive behaviours are restricted; for example, noisy areas can restrict the operation of windows specifically in educational buildings. Secondly, building related factors need to be examined to measure the degree of personal and environmental behaviours occupants can take based on type and architectural features of the spaces; for example, shared spaces in office buildings can restrict operations on controls. Thirdly, occupant related factors should be studied to discover the effect of personal characteristics of occupants and their occupancy patterns; for example, energy saving concerns of residents can restrict their efficient operation on controls.
- The common factor affecting *window operation* in buildings is indoor/outdoor temperature and seasonal changes, with 95% of studies in office, 70% of studies in residential and 63% of researches in educational buildings. This study suggests that considering COB factors in window design can secure different aspects of comfort, such as visual, thermal, acoustic and indoor air quality, and can facilitate safe operation of windows without increasing energy use.
- Confirmed by 70% of studies, the most recurring variable on *shade operation* in office buildings is 'sun effects and orientation'. Shade operation has not received much attention in residential and educational buildings; however, few studies confirm that blinds are adjusted to control sunlight, heat and to darken the room for presentations in educational buildings. Blinds should be easy to use, accessible and user-friendly for frequent operation to provide more comfort and save energy.
- The most recurring variable on *light operation* in office buildings is primarily arrival and departure patterns, confirmed by 60% of sampled studies, and then illuminance level. However, not many researches are done in residential and educational buildings. For intermittent operation on lights, local lighting controls can be designed or the number of occupants sharing an office can be reduced, encouraging light operation when light level is low to save energy.
- Studies on doors, fans, air conditioners and heating systems are not as comprehensive as studies on other controls such as windows, blinds and lights. However, most reviewed researches show that their operation is related to indoor/outdoor temperature. Similarly, these controls should be designed and selected based on COB factors and it should be possible to override them, if needed.
- Studies on personal behaviours are not developed compared to studies on environmental behaviours, especially in residential buildings where residents can take different personal behaviours. Changing clothing level as one of the most important personal behaviours is shown to be mostly correlated with outdoor temperature in office buildings and with 'long term trend in temperature' or 'sequence of temperature' in educational buildings. Changing policies towards personal behaviours within acceptable limits and promoting them can provide higher level of comfort and decrease energy use.

#### 3.2. Adaptive behaviours and Affected Factors (ICE Factors)

The second part of this paper, group B studies review the effect of adaptive behaviours on indoor quality, energy consumption and comfort (ICE factors).

### 3.2.1. Adaptive Behaviours and Indoor Quality

Adaptive Behaviours help occupants feel more comfortable by changing the quality of indoor environment. Several studies have shown that using the means of controls like windows and fans in office buildings can improve air movement and consequently decrease peak operative temperature [8], [9], [106], [162]. Environmental variables in residential buildings also get improved by the operation of window, door [109], [119], [163] and fans in summer [119], and by heating systems in winter [109]. There is a large difference between ‘basic ventilation’ during un-occupancy with closed windows and doors, and ‘user-influenced ventilation’ during occupancy with operation on windows and doors [130]. Low air exchange rates and consequently high indoor concentrations of air contaminants are found in California homes as 10% of 63 homes did not open their windows/doors at all and only 16% opened their windows with doors being open less than an average of 0.05 m<sup>2</sup> [121]. In educational buildings, the efficacy of improving indoor air quality by opening windows is significantly influenced by location of the school, climatic conditions, occupants’ behaviour towards controls, and classroom’s and windows’ design [164]. Indoor air quality in primary schools with manual operation of windows is significant, especially during heating seasons [148], [165]–[168], when most of windows are closed to save energy [154]. Therefore, it is important to facilitate adaptive behaviours towards windows during all seasons to provide indoor quality, especially during heating seasons when window operation is lower [165], [169]. Studies show that night ventilation, pre-ventilation and cross-ventilation can improve indoor air quality [150], [170] and not practising efficient adaptive behaviours can result in poor indoor quality [121], [160].

### 3.2.2. Adaptive Behaviours and Occupants’ Comfort

From the biological perspective, if opportunity is provided human being interacts with the environment to secure and restore their comfort [171]. According to the adaptive approach by Nicol and Humphreys (2002), “if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort” [11]. Table 5 shows how adaptive behaviours affect comfort in office, residential and educational buildings. Generally, higher levels of comfort and satisfaction are observed when type and level of controls are considered to provide efficient, easy and accessible operations on occupants [20], [52], [68], [41], [78], [89], [172]–[177] and when occupants can take personal adaptive behaviours [144], [157], [178]. Thermal and visual comfort are significantly affected by type of windows and shades and their efficient operation. Size and type of windows are key factors for providing thermal comfort for occupants, connecting inside to the outside and maintaining natural ventilation [4]. Occupants usually control shades to improve visual comfort than thermal comfort [67], because visual stimuli like glare provokes a more immediate behaviour change than thermal or olfactory stimuli [179]. However, Ne’eman et al. (1984) shows that office occupants rate controls over visual comfort among the least important ones and controls over thermal comfort as the most important ones [180]. Studying the effect of personal behaviours on comfort has shown that 27% of students in primary schools in UK could improve their thermal comfort vote by putting on or off their jumper or cardigan [144].

Table 4. Effect of adaptive behaviours on **comfort** in office, residential and educational buildings

	Study	Country	Outcome of the study	How facilitating efficient adaptive behaviours
Office	[20], [52]	CH, US	Occupants' comfort temperature increases as their control over the environment increases.	Higher level of visual comfort, thermal comfort, indoor air quality and satisfaction is reported by having more access to user-friendly and easy to use controls.
	[172]	Finland	Low comfort levels are due to low level of control over room temperature, few adaptive opportunities and difficult to use thermostats.	
	[178]	France	Thermal comfort is affected by operations on set point temperature, clothing insulation, and blinds.	
	[19]	US, Canada, Finland	Occupants with and without access to windows show average air quality satisfaction vote of 0.48 and 0.14, respectively. Occupants with access to thermostats show improvement in satisfaction of 0.93.	Mode and type of controls are significant factors to achieve comfort and satisfaction among occupants. Automatic controls should be easy to use and occupants should be able to override them if needed.
	[55]	UK	The highest level of comfort is observed in an office with user-friendly windows and the lowest degree in an office with high glazing-to-wall area ratio.	
	[181]	USA	Satisfaction is higher among occupants who know how to operate automatic blinds.	
	[58], [69], [70]	US, JP, FR	Higher levels of visual comfort can be provided by providing outside views.	To avoid conflicting situations among occupants, individual controls for each station can be designed or the number of occupants sharing a control can be reduced. By providing individual controls, occupants can adjust their preferred outside view and lighting level, which increases visual comfort and reduces light-related health problems.
	[68], [175]	NL, CA	Occupant's state of comfort is influenced by controls' availability, mode and level of control.	
	[40]	Washington	Dissatisfaction and stress is caused by occupants' inability to access controls, resulting in light-related health problems such as migraine.	
	[89]	California, UK	Occupants' satisfaction over controls is affected by mode of controls, with 85%, 78% and 57% of occupants finding manual, semi-auto and auto mode of lighting comfortable, respectively.	Increasing freedom for taking more personal behaviours can also provide higher levels of comfort.
	[174]	Belgium	Discomfort is reported when automatic systems make sudden and unexpected changes or when occupants are negatively affected by behaviours of others in their environment.	
	[78]	UK	Discomfort is reported due to automatic blinds that operate at wrong time and create conflicting situations by not allowing individual control for each station, resulting in system deactivation.	
	[176]	UK	Occupants prefer to choose their own lighting environment rather than accepting even the 'better' lighting level chosen for them.	
	[173]	France	Most occupants prefer automatic lighting systems but appreciate having control over the system and being able to switch lights on and off.	
	[91], [177]	UK	Occupants are more dissatisfied where many light fixtures are grouped together and automatic controls are difficult to use, resulting in systems being deactivated.	
Residential	[3]	Germany	Occupants' perception of comfort is improved by opening windows, and is affected by CO <sub>2</sub> level.	Providing more controls for residents can provide higher levels of comfort and make them more tolerable to uncomfortable situations.
	[116]	India	Number of uncomfortable residents decreases from 60% to 7% by taking more adaptive behaviours.	
	[5]	Indonesia	Residents are more tolerable of less comfortable conditions when they can adjust controls.	
Educational	[157]	England	Students feel more comfortable if they can change clothing level and metabolic rate (posture and activity). Sometimes constraints on clothing can cause 4°C departure from the optimum temperature.	Students can reach higher levels of comfort by a short change in type of activity under teacher's permission, or by changing clothing level within acceptable limits in times of discomfort.
	[182]	Canada	Satisfaction is higher when students have access to lighting controls. The more important daylight is to them, the more they want to control it.	

Table 5. Effect of adaptive behaviours on **energy consumption** in office, residential and educational buildings

	Study	Country	Outcome of the Study	How facilitating efficient adaptive behaviours
Office	[176]	UK	Energy can be saved by installations that allow user control without affecting negatively occupant's perception of visual environment.	Energy can be saved when occupants have a positive perception over controls and have an ability to operate them easily. Therefore, type and design of controls is significant for energy consumption. Appropriate design of windows and blinds with effective operation, can control the energy needed to maintain thermal and visual comfort by inviting more daylight and controlling solar radiation. Lighting energy can also be reduced by easy-to-access, easy-to use dimmable electric lights and well-programmed occupancy sensors. Mixed-mode ventilation than mechanical ventilation can provide higher levels of comfort and save more energy.
	[178]	France	Total energy demand is mostly affected by operations on set point temperature, blinds and lights.	
	[8]	UK	Annual heating energy demand can be reduced by adding thermal mass to shading.	
	[91]	UK	Where controls are complex to use occupants choose lighting levels that reduce the need for using controls, resulting in increased energy consumption.	
	[41]	Indiana, USA	Lighting energy can be decreased by easy-to-access dimmable electric lights and motorized roller shades as daylight utilization is increased.	
	[60]	UK	Increased use of electric light is due to over glazed building as blinds are down most of the time.	
	[59]	Wisconsin, USA	Energy saving is reduced by 30 percent by relying on occupancy sensors for switching lights off than switching them off immediately after leaving office.	
	[62]	Austria	Electrical energy use for lighting can be reduced to 66-71% by using occupancy sensors and daylight-responsive dimming devices.	
	[183]	USA	Substantial HVAC energy savings can be provided by using mixed-mode ventilation for core zones.	
Residential	[184]	Spain	Peaks of energy consumption occur in the morning and at night as occupancy rates are higher and there is no or little sunlight. The peaks can be lowered by using LED technology; replacing 50% and 80% of lamps with LED technology results in 40% and 65% energy reduction, respectively.	To explain differences in energy consumption in residential buildings, physiological, personal, demographic and economic variables should be considered.  Well-insulated buildings and efficient lighting technologies, for example LED technology, can help to reduce energy. Operation of controls is facilitated when controls save more energy and remove energy saving concerns of residents.
	[32]	Footnote <sup>4</sup>	Heating demand can be quantified by the effect of window use in uninsulated (5 to 13%), moderately insulated (15 to 33%) and well insulated dwellings (25 to 50%). Heating demand is mostly affected by occupant behaviour toward windows in well insulated buildings (25 to 50%).	
	[185]	Greece	The differences toward energy consumption for heating space can be explained by physiological, personal, demographic and economic variables like respondents' age, family size, dwelling size, occupancy patterns and income.	
	[99]	Netherlands	Energy consumption is more affected by the number of hours that the heating system is in operation than by temperature setting.	
Educational	[153]	An open plan studio, US	More energy can be saved and better daylight conditions can be provided by using a subdivided window than by using unified window design. Averagely, 2 hours less electric light is used per day by using light shelves.	Subdivided windows can secure different aspects of comfort, visual, thermal and air quality, and can save energy due to providing more natural light. Night ventilation can reduce cooling costs next day, therefore, designing secure windows for night ventilation is important (Providing windows in different sizes and designs).
	[152]	UK	Energy consumption is affected by closing blinds as occupants keep artificial light on most of the time to provide adequate amount of light.	
	[170]	School in Germany	Energy use depends on the room temperature set-point and occupancy; energy costs for cooling for the next day can be reduced by night ventilation.	

### 3.2.3. Adaptive Behaviours and Energy Consumption

Calculating and simulating building energy performance without considering occupant behaviour results in error [186]. Careless behaviour can add one-third to the energy consumption of the building [187] while appropriate behaviour can save one-third [188]. Sonderegger (1978) shows that 71% of the unexplained variation for space heating in 205 townhouses in Twin Rivers is caused by occupant's energy consumption patterns [189]. Therefore, to address the issue of energy consumption in housing, residents and their behaviours should be considered in studies [189]. Bourgeois, Denis et al. (2006) show that active occupants that rely on daylight than the ones who constantly use artificial light reduce overall expenditure on energy by more than 40% [190]. Similarly, Hong & Lin (2013) employed building simulations to show that energy saving occupants consume up to 50% less energy while occupants with wasteful lifestyle consume up to 90% more energy than standard occupants [191]. The study by Masoso & Grobler (2010) in six commercial buildings illustrates that more energy is used during non-working hours (56%) than working hours (44%), due to occupants' behaviour of leaving air conditioning systems, equipment and lights on at the end of day [192]. Another study in Canada shows that 66% increase in lighting energy and 33% increase in total energy are caused by inefficient blind use [193]. Even occupants' perception toward environmental controls is found to affect energy savings. Barlow & Fiala (2007) show that positive impression of the occupants towards opening windows, controlling shading and use of localized switching affects energy consumption [100]. Studying the effect of personal behaviours on energy consumption, Newsham (1997) suggests that as clothing flexibility increases, occupants adapt to higher cooling set points and lower heating set points so they save energy without affecting their state of comfort [194]. Generally, total energy saving is increased by allowing user control [176], easy to use controls [41] and efficient design of lights, shadings and windows that provide more daylight [8], [32], [59], [60], [62], [41], [153], [178], [183], [184]. Table 5 shows how adaptive behaviours affect energy consumption across different building usage. The most recurring factors affecting energy consumption in all building use include type and design of controls, occupancy patterns and set point temperatures.

### 3.2.4. Results

Summary of factors that are influenced by adaptive behaviours including indoor environment, comfort and energy consumption (ICE factors) are listed in the following.

- To provide indoor quality, it is important to facilitate adaptive behaviours towards controls in all seasons, especially during heating seasons when windows are less in operation. The efficacy of improving indoor quality is significantly influenced by design of controls and occupants' behaviour towards controls, therefore, design of controls should provide opportunities for various types of ventilation (e.g. night ventilation, pre-ventilation and cross-ventilation).
- Higher levels of comfort and satisfaction are reported when more personal and environmental adaptive behaviours are provided (i.e. higher level of control). Therefore, individual controls or controls shared by fewer number of people in the space can increase comfort level. Comfort is increased when building's controls are easy to use, accessible and can be overridden, if needed. This also saves energy as controls are operated more frequently and efficiently.
- Energy consumption can be explained by environmental variables, building characteristics, efficiency of the systems and occupants' behaviour. Designing a suitable control system is the most important factor that enables occupants to achieve a higher level of comfort and save energy



in all building use. For example, subdivided windows allow occupants to pick and choose which parts of windows need to be opened or closed to maintain thermal comfort, visual comfort and air quality. In fact, instead of opening a whole window to have fresh air during winter and lose large amounts of heat, only one part of it can be opened for natural ventilation when it is needed.

- Mode, type and design of building's controls are the most recurring factors affecting adaptive behaviours and consequently indoor quality, energy consumption and comfort.
- The importance of facilitating adaptive behaviours can be explained by its effect on indoor quality, comfort level and energy consumption (ICE factors) and its role on achieving a balance between ICE factors. Better indoor quality, more energy saving and high levels of perceived comfort make occupant's perception toward adaptive behaviours more positive.
- Adaptive behaviours can create balance between ICE factors to design more comfortable spaces for occupants without increasing energy demand.

As a result, besides COB factors that should be studied to design/set up adaptive behaviours, awareness of ICE factors influences occupant's perception toward adaptive behaviours. In fact, occupant's positive impression of adaptive behaviours makes them practise adaptive behaviours more effectively.

## 4. Discussion

This study has reviewed factors relating to adaptive behaviours with the aim of developing a design framework for facilitating occupant's adaptive behaviour. Developed framework, derived from overviewing selected studies, consists of three stages:

The first stage is to examine the influence of context, occupant and building related factors (COB factors) on adaptive behaviours and study how adaptive behaviours impact on indoor quality, comfort and energy (ICE factors), with relation to each other. This study shows scenarios in which adaptive behaviours happen, change in frequency and time, and are restricted/facilitated with relation to COB factors. On the other hand, adaptive behaviours by affecting ICE factors and improving built environment can encourage occupants in adaptive behaviours. Adaptive behaviour can also be implemented in design process to achieve a balance between ICE factors. Therefore, ICE factors should also be explored to facilitate *suitable* adaptive behaviours.

The second stage is to design user friendly and efficient buildings' controls for environmental behaviours and set up strategies for practising suitable personal adaptive behaviours and find a balance between these two. Designing controls and setting up strategies for personal behaviours should be based on findings from the first stage to find out how adaptive behaviours turn discomforting conditions to comforting conditions. Balance between personal and environmental behaviours can be achieved by 'doing more personal behaviours when environmental behaviours are restricted' and by 'doing more environmental behaviours when personal behaviours are limited'.

The third stage of the framework is running Post Occupancy Evaluation (POE) to control the performance of proposed adaptive behaviour. Providing opportunities for adaptive behaviours does not guarantee occupant's efficient adaptive behaviour. POE is required to find out how occupants interact with controls, in what sequence occupants take adaptive behaviours, and to predict how behaviours affect ICE factors. Results of post-occupancy evaluations obtain influential factors on adaptive behaviours, which can again be used in the first stage of framework to design future buildings

more efficiently. Post-occupancy evaluations can also educate occupants to interact more efficiently with controls and to take appropriate personal adaptive behaviours. Based on above three stages, a design framework is advised to be considered as part of design process for providing efficient adaptive behaviours, which can be found in Fig 3.

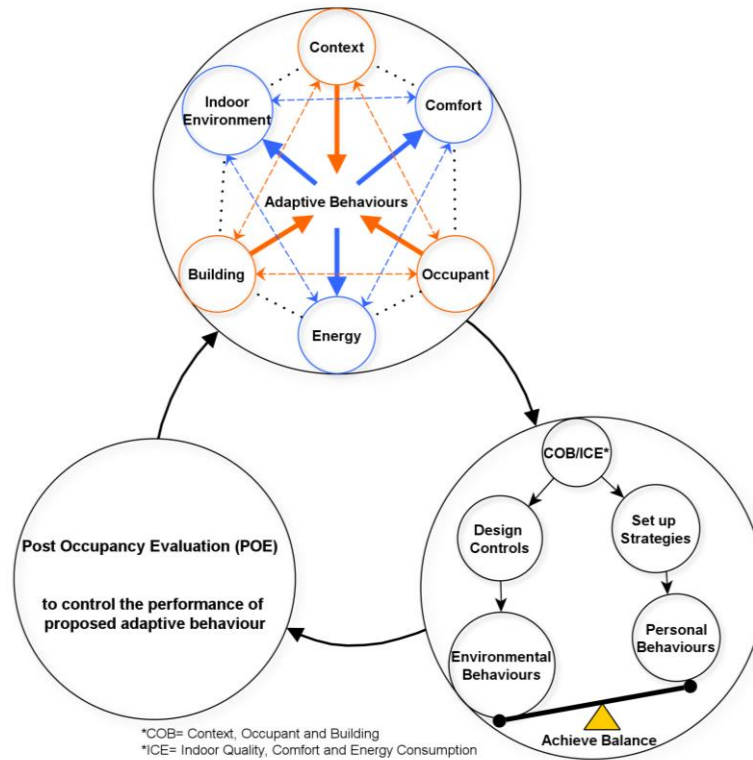


Fig 3. Proposed Framework as part of design process to facilitate adaptive behaviour

Future studies should focus more on the performance of adaptive behaviours in *educational buildings*, especially among *children*, while existing studies are mainly focused on adults in residential and office buildings. Research on adaptive behaviours towards integrated aspects of comfort needs to be expanded as well since different thermal, visual, air quality or acoustic stimuli influences adaptive behaviours differently. Furthermore, the sequence of taking adaptive behaviours can be different in different building use [5], [7], [195] and its sequence can change energy consumption of the buildings [117]; therefore it is also important to find out in what sequence occupants adjust themselves or the environment to reach comfort.

## 5. Conclusion

This study has reviewed researches on adaptive behaviour of occupants in different building use with the aim of developing a framework that is advised to be considered in design process. The first part of the paper studies the influence of three factors of Context, Occupant and Building (COB factors) on both environmental and personal adaptive behaviours to discover the occurrence and change of the adaptive behaviours. The second part reviews studies on the effect of adaptive behaviours on Indoor environmental quality, Comfort and Energy consumption (ICE factors) to find out how the relation between these factors can be balanced by adaptive behaviours and how occupant's perception of behaviours can be improved. Based on this review, the authors introduce a framework that urge building designers to consider all related factors holistically to facilitate occupants' behaviour.

Therefore, designers should evaluate how adaptive behaviour is influenced by COB factors and impact on ICE factors at the first stage of this framework. According to the factors studied in the first stage, efficient and user-friendly controls are designed for environmental behaviours and strategies are set up for practising personal behaviours in the second stage. Personal and environmental adaptive behaviours complement each other; therefore, one can be exercised more when the other one is restricted. The performance and efficiency of adaptive behaviours are controlled through Post Occupancy Evaluation (POE) in the third stage. This framework can be used as a part of design process by building designers to facilitate adaptive behaviours and create a positive influence on built environment.

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