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Comprehensiveness and usability of tools for assessment of energy saving measures in schools

Greta Caruana Smith[1], Dejan Mumovic[1] and Lee Curtis[2]

Abstract

Having in mind constantly changing regulatory frameworks which demand both carbon emission reduction and improvement of the quality of internal environment, this paper analyses strengths and limitations of available design tools of various complexity: Annex 36 Energy Concept Advisor Tool and an approved Dynamic Simulation Model. As a platform for discussion, two representative school buildings in North London were selected and modelled using both tools. Discussion integrates views of 76 building industry professionals on applicability of various school retrofit options in practice. Using the available statistics on total number of schools and floor space in each category, a simple extrapolation was applied to roughly quantify potential for carbon emission reduction of the school building stock in England and Wales.

Practical applications: More than 70% of approximately 25,000 maintained and independent primary and secondary schools in England and Wales were built before the introduction of thermal regulations in 1970s, offering a significant opportunity to reduce carbon emission of the school building stock. In terms of construction, they could be divided in two major categories: pre 1919 solid wall construction and post war masonry cavity school buildings. This paper reviews capabilities of the less-known Energy Concept Advisor which offers designers, architects and decision makers the opportunity of assessing the performance of a particular building and comparing possible retrofitting measures quickly.

Keywords

Refurbishment, schools, thermal modelling, energy, retrofit options

Introduction

Nationally, schools alone are responsible for 15% of the total energy consumption in public and commercial buildings.[1] Locally, schools in England contribute to around 40–60% of a Local Authority's (LA) carbon emissions[2] and as such provide a substantial financial burden on the LA's carbon tax payment. There are approximately 25,000 maintained schools in

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[1] The Bartlett School of Graduate Studies, University College London, UK
[2] Cundall, London, UK

Corresponding author:
Dejan Mumovic, The Bartlett School of Graduate Studies, UCL, 14 Upper Woburn Street, WC1H 0NN London, UK.
Email: d.mumovic@ucl.ac.uk

England and Wales with a total school area of 60,000,000 m^2 and a replacement value of £130 billion.[3] In addition to a £1.5 billion annual spend on maintenance of school buildings, the annual spend on energy in year 2006–2007 exceeded £420 million. With an aim to reduce carbon emission by 80% against the 1990 baseline by 2050[4] and to firmly embed the principles of low carbon economy in the hearts and minds of future generations, the UK government seeks to address the issue of school's carbon emission. In light of this and considering the significant number of existing schools that are still in use, improving the energy performance through sustainable refurbishments is fundamental in order to meet the set carbon emissions target.[5] This paper therefore focuses specifically on the refurbishment of school buildings.

In classrooms, indoor environment quality performance is dependent on how the building responds to variations in internal and external conditions and on how and when the pupils and teachers respond to these variations, i.e. what adaptive actions they take and under what conditions they take them.[6] Classrooms usually have high internal heat gains attributed mainly to high occupancy density, which are of a transient nature as pupils come and go and from lighting that changes from class to class depending on the teaching methods used. Classrooms also need to perform well acoustically, both for the spoken word and for music, and as sound amplification is generally not used, background noise control is critically important. All these factors, in addition to energy use, place constraints on, for example, the ventilation design; if this is poor, it can lead to the deterioration of indoor air quality (IAQ) and thermal comfort[6] that could affect pupils' health and performance.[7,8] Refurbishment projects place another set of constraints related to spatial organisation and limited number of retrofit options. Having this in mind, this paper aims to:

- establish the key issues with respect to refurbishment school projects including the existing knowledge, suitability of existing guidelines and regulatory documents
- analyse the strengths and weaknesses of two design tools of different complexity: Annex 36 Energy Concept Advisor (ECA) and an approved DSM software – Thermal Analysis Software (TAS)
- roughly quantify potential for carbon emission reduction of the school building stock in England and Wales

Methodology

The methodology was split into two stages:

- in the first stage an online questionnaire was sent to 1200 members of the CIBSE School Design Group, of which 76 professionals responded. These members represent UK-based professionals who have been working and researching in the field of low carbon building design with specific interest in the education sector
- in the second stage of the study, a detailed modelling was carried out to analyse suitability of two design tools of various complexity: ECA and TAS. Using the available statistics on total number of schools and floor space in each category, a simple extrapolation was applied to roughly quantify potential for carbon emission reduction of the school building stock in England and Wales.

Stage one: Online questionnaire

Although the authors have identified some critical issues of importance to school building refurbishment conducive to learning based on the previous research experience in this area, these were further substantiated through the questionnaire. The questionnaire consisted of 30 multiple-choice questions divided into three key categories, which were identified in collaboration with Cundall. The questionnaire addressed three main points:

- adequacy of available guidelines and tools aimed to aid designers and engineers when looking into energy-efficient retrofitting of schools
- how refurbishment of listed school buildings differ to refurbishment of non-listed schools
- the extent to which facilities management can contribute to lower carbon emission in schools

Initial data analysis was carried out to identify two 'sample representative' engineers within Cundall with the aim of understanding the opinion of the industry about energy-efficient refurbishment of schools in practice. The interviews with selected engineers were used to identify the following:

- optimum refurbishment solutions
- critical stages within the design process
- the design tools and guidelines available
- the main challenges involved in the sustainable refurbishment of listed school buildings.

Stage two: Building simulation

The aim of the simulation analysis was to study the benefits and limitations of two software packages of various complexity. Approved DSM software, TAS, has been selected as it is widely used in the UK for dynamic building thermal modelling and is an approved Part L compliance tool.[9] It has to be noted that use of Simplified Building Energy Model (SBEM) was disregarded as both buildings have distinct properties that behave non-linearly over the periods of the order of an hour, such as ventilation with enhanced thermal coupling to structure. Furthermore, approved DSM software are also more suited as design support tools as opposed to SBEM as compliance calculator. On the other hand, ECA, which was developed by the International Energy Agency (IEA) as part of Annex 36, has been selected as it was designed specifically for refurbishment of school buildings with special reference to energy use.[9] It was therefore modelled to address typical school constructions and common scenarios encountered when refurbishing such building types. ECA is however not well-known in the UK building design industry. Although both packages give energy loads for a modelled building, their aim is also different. Despite this they can both be used effectively at different stages in a project potentially making a refurbishment more efficient both in terms of energy savings and feasibility. Usability of the UK version of ECA has never been tested against more complex dynamic thermal simulation tools.

A large school in North London was selected as the case study as it consisted of pre 1919 and post-war buildings, where the former consists of solid wall construction of Edwardian style and the latter consists of masonry cavity construction following the SCOLA/CLASP building systems.[10] Although none of these buildings are listed, the school lies within a conservation area, which implies that alterations should be sympathetic to the original character of the building.[11]

Building A was built in 1908 and as such follows the Edwardian school building morphology (Figure 1). It is a central corridor building with a gross floor area of 4200 m^2, consisting of three storeys and a lower ground floor. Thick brick walls, pitched roofs and large, timber-framed windows are characteristic of this building style. The sliding, vertical sash windows are single glazed and in general each classroom has two windows giving a glazing ratio of 0.3. Classrooms have an average internal floor area of 47 m^2 and seat approximately 25 students.

The building is heated by two gas-fired boilers, which were replaced in 1993 and are connected to cast-iron radiators with a manufacturers' declared efficiency of 78%. A central thermostat controls the radiators that have no individual control and cannot be regulated. Water flows at a temperature of 55–60°C. In general, the heating is turned off by night;

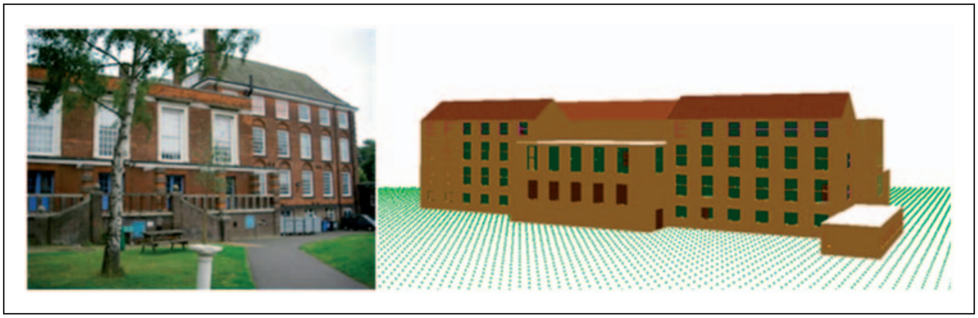

Figure 1. Building A

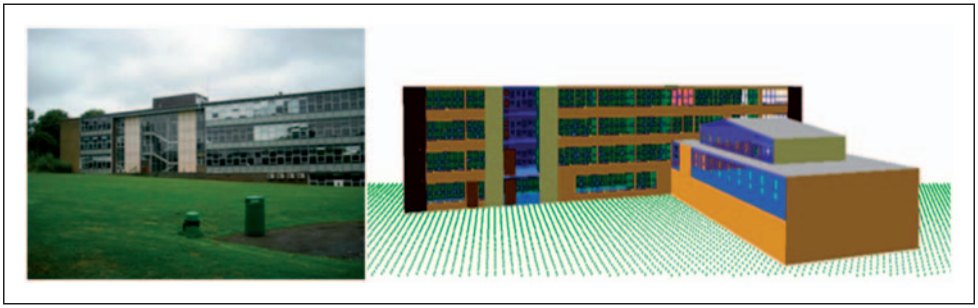

Figure 2. Building B

however, on very cold days it is left to operate throughout. Domestic hot water is also supplied by a gas-fired boiler, which was replaced in 1994. Water is maintained above 60°C to minimise the risk of waterborne legionella contamination.

Ventilation takes place naturally by manually opening the windows; therefore, no mechanical systems are installed. South facing rooms however are equipped with fans that are used during the warmer days for comfort cooling. Curtains or internal blinds are used to control solar penetration.

A typical classroom has nine 58 W fluorescent lamps suspended from the ceiling. The lamps were replaced in 2004 with energy-efficient electronic ballast ones. Wall switches control the lighting manually.

Building B (Figure 2) was constructed in 1955 and has a gross floor area of 5400 m^2. The three-storey building is a central corridor type supported by a steel structure and concrete walls with a fully single-glazed curtain walling. A low plastered brick wall is constructed internally in each floor and lies just behind the glazing. The metal framing was painted over several times and as a result not all windows close tightly. On average, 25 students form a classroom, which has an internal area of 46 m^2 and an approximate glazing ratio of 0.7.

Heating is supplied by two gas-fired boilers that were replaced in 2002 and have a manufacturers' declared boiler gross efficiency of 84%. The boilers are connected to cast-iron radiators that are controlled by a central thermostat and circulating water is maintained at a temperature of 65–70°C. Hot water is also supplied by two gas-fired boilers that were replaced in 2009.

Ventilation takes place naturally by opening windows that are controlled manually by the occupants. The windows have a horizontal pivot and are middle hung therefore the opening area is equal to the window area. South facing classrooms are also equipped with two fans for comfort cooling. ICT labs are cooled by local split type heat pumps.

Artificial lighting is provided by seven 58 W suspended fluorescent lamps with electronic ballasts and local manual control. Solar gains are controlled by opaque internal blinds, which are often closed during warm days due to the high solar gains, thus reducing daylight levels considerably.

Both school buildings were simulated in TAS and ECA. The initial values of input parameters reflect the actual environmental conditions of the two buildings and were based on observations from site visits and available documentation (Table 1). The parameters examined were classified into three categories:

- general construction and HVAC (infiltration rates, thermal mass, heating system efficiency)
- construction elements (external walls, glazing, roof, ground)
- use (occupant density, thermostat heating set point, daytime ventilation rates, night ventilation rates, heating schedule, lighting gains and small power gains)

Based on these results, ECA suggests a number of possible retrofitting measures for the building envelope, HVAC and lighting systems. Since TAS does not simulate artificial lighting, the tested retrofitting measures exclude improvement to the lighting system. A comprehensive differential sensitivity analysis (DSA) was carried out using both design tools in order to further analyse building performance issues highlighted in the questionnaire and to assess the impact of each retrofit measure suggested by ECA on the energy consumption.

The DSA involves the variation of one ‘retrofit’ input parameter in each simulation, with other inputs remaining at their base case values. This allows the modeller to measure the direct impact that changes in the input parameter have on the output value. The tested retrofitting measures in Table 2 were dictated by those measures recommended and available in ECA. The package was developed in Germany and although it has been adapted to reflect the UK school estate, the recommended retrofitting measures are still based on German regulations and therefore do not consistently adhere to requirements outlined in UK Building Bulletins.

Having tested the measures separately, the cumulative effect was tested by combining a number of individual measures into one scenario and re-testing. Finally, the results obtained in TAS and ECA for each simulation were compared and discussed.

Results and discussion

Stage 1: Industrial views

The main questionnaire findings are summarised in Figure 3. A detailed analysis of all results is given elsewhere.[12] Ideally, the response rate should be higher, but it is encouraging that only a few answers were not equal to pre-specified category based on the authors’ knowledge of the industry. Based on both the online questionnaire and detailed interviews with selected engineers, in general, the delivery of low carbon building refurbishment is considered possible, but the study indicates that currently there is a lack of (a) adequate awareness regarding the emerging technologies available for low carbon school retrofit commercially, (b) reliable database of recently refurbished schools at present that would provide this type of information and (c) recent good engineering practice guides.

Nonetheless, professionals believe that looking into energy-efficient solutions at an early stage enables the designer to incorporate measures within the given budget. At present, the main barrier to exploring potential low carbon technologies is the economy associated with it. There is undue emphasis on capital costs rather than the life cycle cost of technology. Resources and research grants available are limited.

Table 1. Thermal Analysis Software (TAS)/Energy Concept Advisor (ECA) input parameters

Input values for the base case of School A and School B

Building	School A	School B
General construction and HVAC		
Infiltration (ACH)	0.45	1.05
Concrete conductivity (W/m.K.)	1.13	1.13
Brick conductivity (W/m.K.)	0.80	0.70
Heating system efficiency	78%	84%

Construction elements

Building	School A		School B	
Parameter	Build up	U-values, W/sq.m.K.	Build up	U-values, W/sq.m.K.
External wall	Plaster/450 mm brick	1.3	Plaster/152 mm brick/102 mm brick	1.5
Glazing	10 mm clear glass	5.6	10 mm clear glass	5.6
Glazing frame	Timber frame	2.8	50 mm metal frame	5.8
Roof	200 mm concrete/50 mm screed/25 mm plastic tile	2.5	25 mm soffit/air cavity/200 mm concrete/50 mm screed/bitumen felt	0.9
Ground	25 mm plastic tile/50 mm screed/200 mm concrete	2.3	25 mm Plastic tile/50 mm screed/200 mm concrete	2.3

Use

Building	School A	School B
Occupancy density in classrooms (people per m^2)	0.53	0.54
Thermostat heating set point (°C)	23	23
Daytime ventilation rates (ACH)	6.05	5.45
Heating schedule	6:00 to 19:00	6:00 to 19:00
Lighting gains (W/m^2)	12	12
Small power gains (W/m^2)	5	5

Considering maintenance costs and payback periods at decision stage also encourages investment in low carbon and renewable systems, which might otherwise be ruled out. This would allow appropriate solutions to be implemented according to the building type and budget. In light of this, tools such as ECA specifically target these aspects by providing a database

Table 2. Summary of applied retrofit measures

Retrofit measure	School	Description	U-Values, W/m^{2}K
Tested retrofitting measures in Thermal Analysis Software (TAS) and Energy Concept Advisor (ECA) for School A and School B			
Insulation second floor ceiling and flat roof	A	Add expanded polystyrene – 60 mm internally/ 100 mm externally/ 200 mm externally	0.54/0.35/0.19
	B	Addition of expanded polystyrene – 60 mm internally/200 mm externally	0.322/0.19
External wall	A	Add expanded polystyrene – 60 mm internally/ 120 mm externally/ 200 mm	0.43/0.26/0.17
	B	Addition of expanded polystyrene – 60 mm internally/120 mm externally/200 mm externally	0.46/0.25/0.17
Glazing	A	Replace with double glazed low-e coating and reduce infiltration to 0.35 ACH.	1.7/1.3
	A	Replace with triple glazed low e coating and reduce infiltration to 0.35 ACH.	0.8
Glazing and cladding	B	Addition of 60 mm polystyrene internally in opaque areas and replacement of glass with double glazing and low-e coating. Infiltration 0.45 ACH	0.46 & 1.7
	B	Addition of 120 mm polystyrene externally in opaque areas and replacement of glass with double glazing and low-e coating. Infiltration 0.35 ACH	0.25 & 1.3
	B	Addition of 200 mm polystyrene externally in opaque areas and	0.17 & 0.8

(continued)

Table 2. Continued

Retrofit measure	School	Description	U-Values, W/m^{2}K
		replacement of glass with triple glazing and low-e coating. Infiltration 0.25 ACH	
Ground	A & B	Add 40 mm mineral wool and screed floor.	0.75
Building fabric complete: Min. retrofitting measures according to ECA	A & B	Addition of 60 mm polystyrene internally to roof and walls, 40 mm mineral wool ground insulation, installation of double glazing with low-e coating and reduction of air infiltration to 0.25 ACH.	
Building fabric complete: Max. retrofitting measures according to ECA	A & B	Addition of 200 mm polystyrene externally to roof and walls, 40 mm mineral wool ground insulation, installation of triple glazing with low-e coating and reduction of air infiltration to 0.2 ACH.	
Heating	A & B	Replacement of boiler with low temperature boiler 70/55°C. Insulation of pipework, replacement of circulation pump and thermostatic control valves. System efficiency increased to 85%.	
	A & B	Replacement of boiler with condensing boiler 55/45°C. Insulation of pipework, replacement of circulation pump and thermostatic control valves. System efficiency increased to 85%.	
	A & B	Replacement of boiler with condensing boiler 35/28°C, insulation of pipework, replacement of radiators, replacement of circulation pump and thermostatic control valves, installation of zone control valves and gross efficiency increased to 85%.	
Ventilation	A & B	Mechanical ventilation with 60% heat recovery.	
	A & B	Mechanical ventilation with 80% heat recovery.	
Lighting	A & B	Replacement with discharge lamps with automatic dimming and occupancy sensors.	
Combined scenario	A & B	Building fabric complete with maximum measures and heating system efficiency of 85%.	

of case studies and the possibility of comparing various retrofitting solutions by looking into not only energy savings and carbon reductions but also capital costs, maintenance costs and pay back periods. In spite of this, ECA is more focused on traditional measures and less on emerging technologies, and its several restrictions might also limit its popularity.

The industry also believes that traditional measures such as introducing insulation and improving the performance of glazing and heating systems are the most cost-effective. Additionally, educating the users on how to operate the building is also essential. The questionnaires also revealed that no one strategy can be applied to a group of buildings. This industrial perception contradicts and limits to an extent the applicability of tools such as ECA, which recommend general retrofit solutions depending on the construction typology.

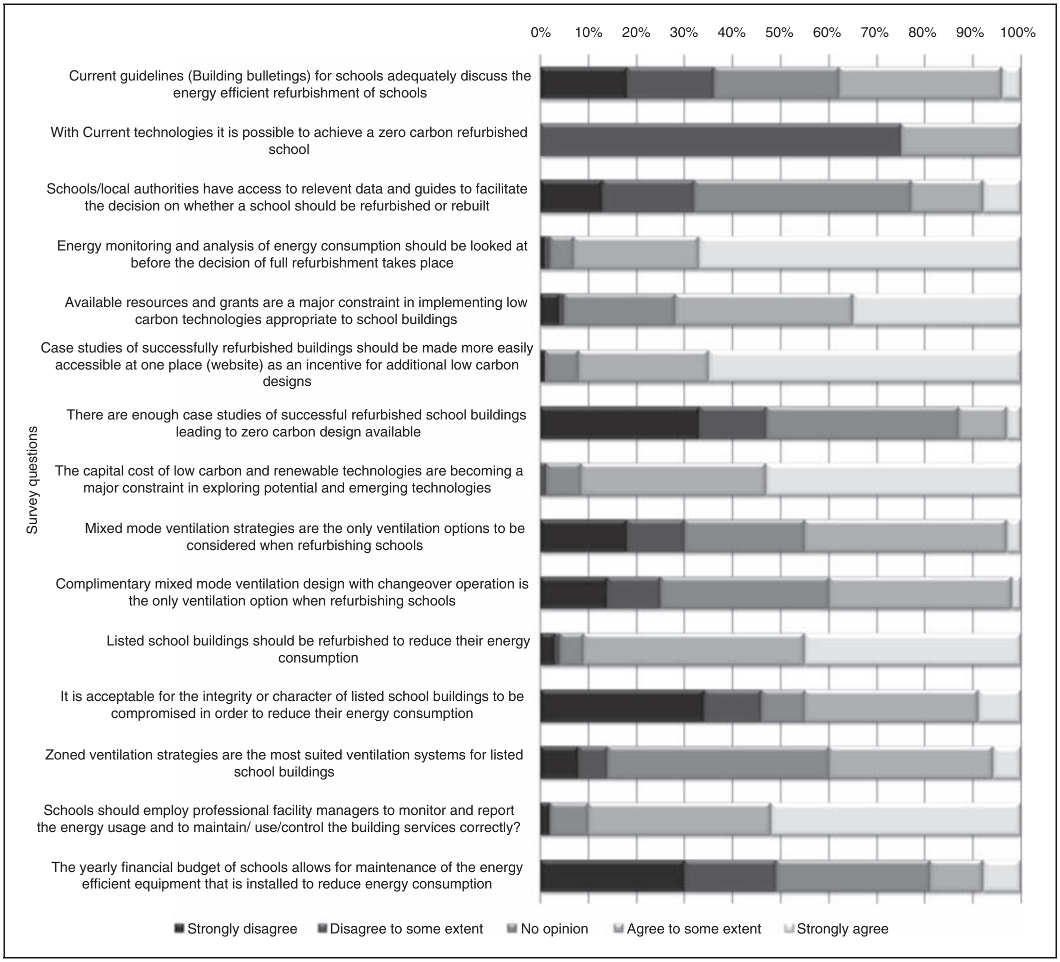

Figure 3. CIBSE School Design Group Members: Overview of the key results

Due to the high occupancy rates in classrooms, providing efficient ventilation in school buildings in order to maintain acceptable CO_2 levels can be quite challenging. Questionnaire results show that mixed mode ventilation systems, both complementary and zonal, are considered to be a suitable strategy for schools although not necessarily the only solution. When looking at possible retrofitting solutions for ventilation in ECA, mixed mode ventilation scenarios and optimisation of natural ventilation systems are not catered for. This poses a significant limitation on the applicability of the software.

Actively managing change to reinforce historic significance, while accommodating the adaptation and change necessary to ensure the continued use of school buildings and spaces, is a key message regarding refurbishment of historic school building stock. This balanced approach adopted by English Heritage[13] will ensure that 22% of school building stock which was built before the WW2 (pre 1919 – 13% and further 9% was built between two world wars) is still fit for purpose. Integrity or character of listed school buildings over energy efficiency is important only to 50% of practicing engineers, which underpins the need for clear

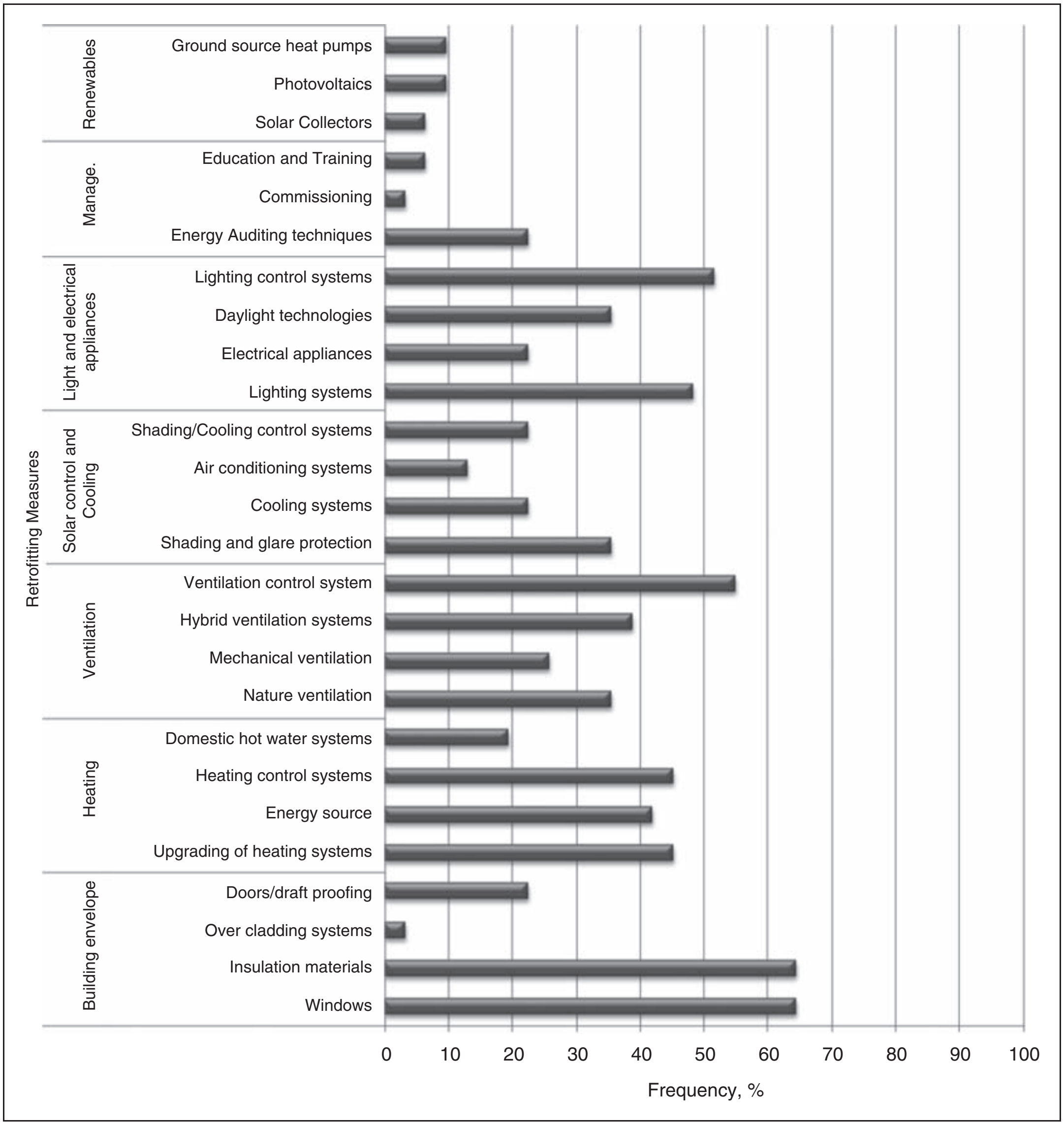

Figure 4. Most common retrofitting measures (based on 33 case studies)

guidelines related to refurbishment of historic school building stock.

The authors reviewed 33 school refurbishment projects across Europe and presented frequency of most common retrofit measures for school buildings (Figure 4). This underpins the views of UK-based building services engineers who pointed out that traditional energy conservation measures such as additional insulation, windows replacement, lighting improvements and upgrading heating systems are the most common and being perceived as the most cost-effective measures.

Optimisation of natural ventilation and implementation of hybrid systems also resulted to be quite frequent. Although in some cases

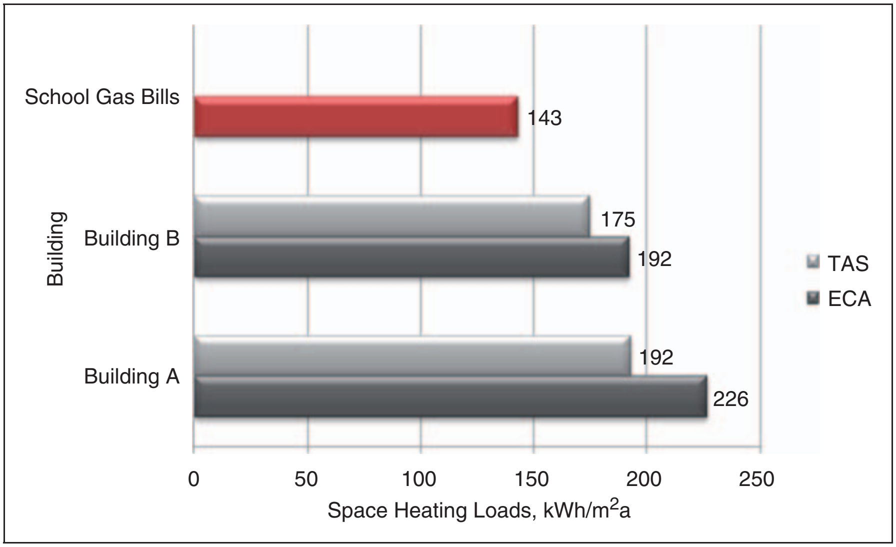

Figure 5. Base case scenario: Buildings A and B

natural ventilation strategies failed due to noise levels and cold draughts, the latter was successfully tackled in a number of schools by pre-heating or pre-cooling the supply air. Mechanical ventilation on the other hand was the least preferred ventilation strategy although quite common in colder countries such as Germany and Finland. Since ECA was developed in Germany, this observation suggests why the software caters only for mechanical systems as a retrofitting option for ventilation.

Finally, improvement of the management systems, use of photovoltaics, solar collectors and ground source heat pumps were the least common interventions even though post occupancy evaluations showed that significant savings can be achieved. These were usually implemented in Mediterranean countries.

Stage 2: Building simulation

Based on the data collected during site visits and available documentation, the buildings were modelled in both TAS and ECA. A comparison was made between the results obtained in each for the existing buildings (base case scenario) and for the proposed retrofitting measures. A detailed analysis of all results and detailed TAS modelling protocol is given elsewhere.[14] Taking into account that ECA is not well-known design tool in the UK, a brief modelling protocol is presented in this paper.

The building was modelled in ECA by selecting given options from drop-down menus and inserting building envelope areas and energy loads as required. Input variables include building typology, orientation, year of construction, location, type of construction of the various elements, heating, ventilation and lighting system and control. Additionally, these variables are limited to typical heating systems and construction types according to the specified year of construction. This offers a very simple approach and however also poses considerable limitations, as the main input variables are restricted. The approach adopted by IEA Annex 36 consortium (developer of ECA) is that the refurbishment of school buildings is primarily driven by the existing construction technology, while practicing engineers in the UK believes that refurbishment options should be based on case by case basis. As a simple design tool, ECA favours

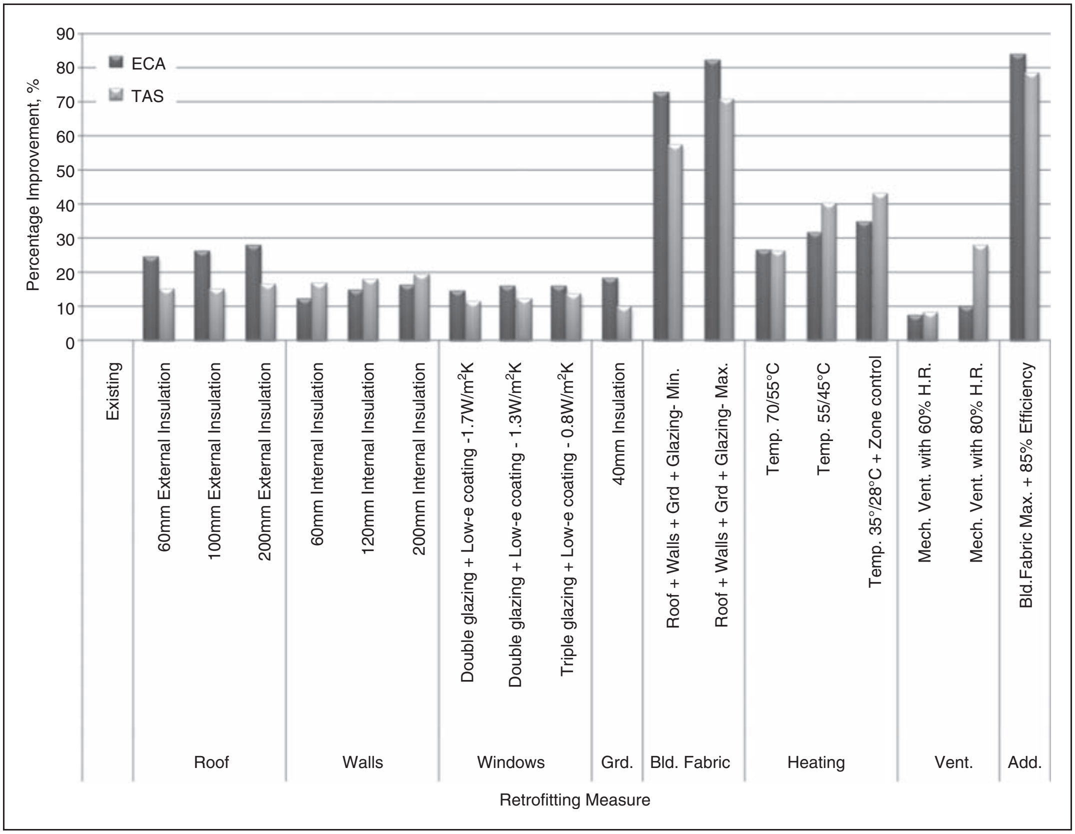

Figure 6. Building A: percentage reduction in the heating load per retrofit measure

conservative and well-tested approach to energy-efficient refurbishment and the decision options embedded in the tool are based on previous good engineering practice. In light of this, the input parameters in TAS were adjusted (mostly calculated U values) to the range available in ECA.

All models are characterised by (a) time resolution, (b) details of building description and (c) physical effects taken into account. Although there is no agreement within the building performance simulation community, the authors believe that if the simulation is limited to well-defined applications and clearly stated results, it is possible to optimise the models to obtain satisfactory results regardless of uncertainties, for example, in boundary conditions or actual operational use, even with relatively simple models such as ECA. Figure 5 compares the space heating load modelled in TAS and ECA for both buildings for the base case scenario defined in Subchapter *Stage two: building simulation*.

A base case model (as 'in use' no retrofit measures) showed that the energy consumption predicted by ECA is consistently higher than that given in TAS by 18% and 11% for the Building A and Building B, respectively. This is a very encouraging result taking into account, for example, that ECA calculations are based on monthly mean temperatures and average monthly solar radiation used for hourly Test Reference Year (TRY) dataset. No attempt was made to adjust the modelled results with

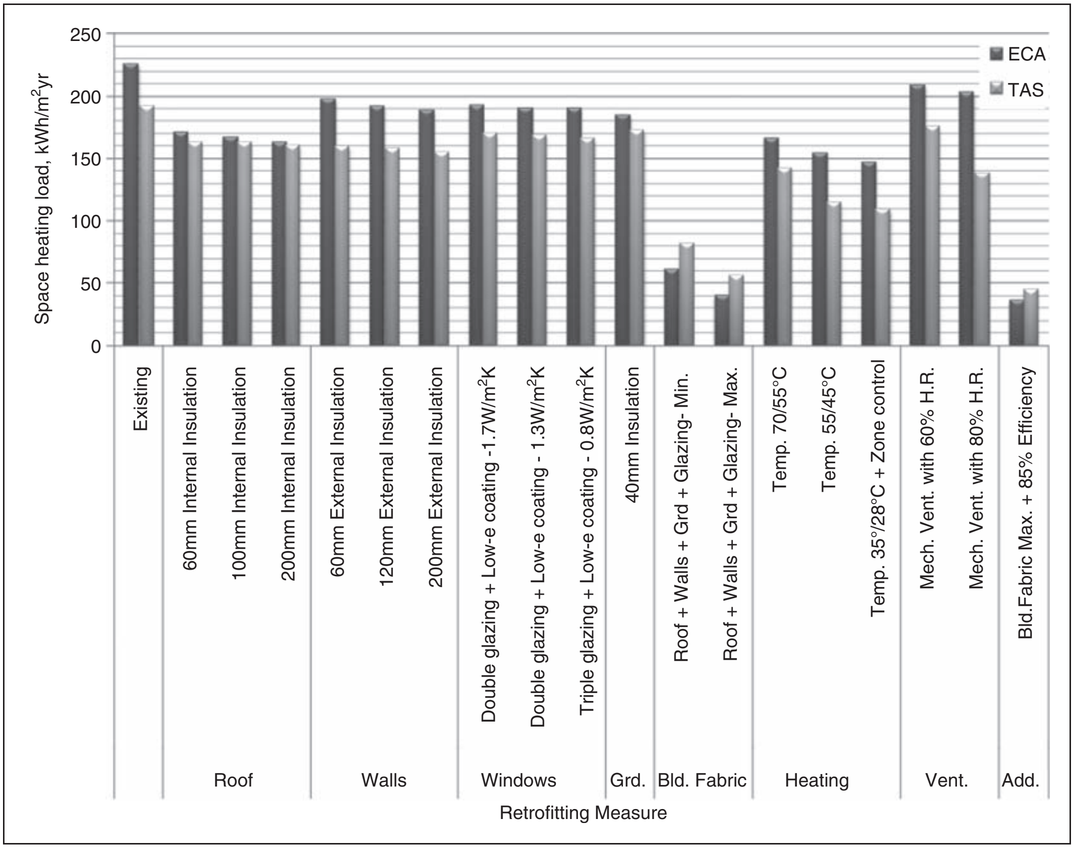

Figure 7. Building A: space heating load per retrofit measure in kWh/m^2/yr

the actual space heating load derived from available gas bills for two reasons: (a) school has a large intermittently used assembly hall and (b) a few relatively large intermittently used workshops both with no gas sub-metering.

Figures 6 and 8 illustrate the percentage improvement and Figures 7 and 9 illustrate the space heating load in kWh/m^2/yr of each suggested retrofitting measure given by TAS and ECA for Building A and Building B, respectively. On comparing the results, thermal improvement of the individual measures gave a percentage reduction of the heating load in the range of 10–19% with TAS and 12–28% with ECA for those measures related to the building fabric. By combining the various measures into one scenario (i.e. insulation, triple glazing, improved boiler performance and mechanical ventilation), the percentage reduction in heating load increased to a maximum of 78% and 79% with TAS and 84% and 90% with ECA for Building A and Building B, respectively.

ECA showed a higher percentage reduction particularly when adding insulation to the roof. Although, none of the tools is explicit in terms of algorithms embedded within the code, overall the scope for carbon reduction due to roof insulation is relatively lower in comparison to the carbon reduction achieved by retrofit of external walls, windows and better control of ventilation losses.[15] Insulating the ground floor was also quite effective as a reduction in load of 10% in TAS and 18% in ECA was predicted. For most retrofit options ECA shows a

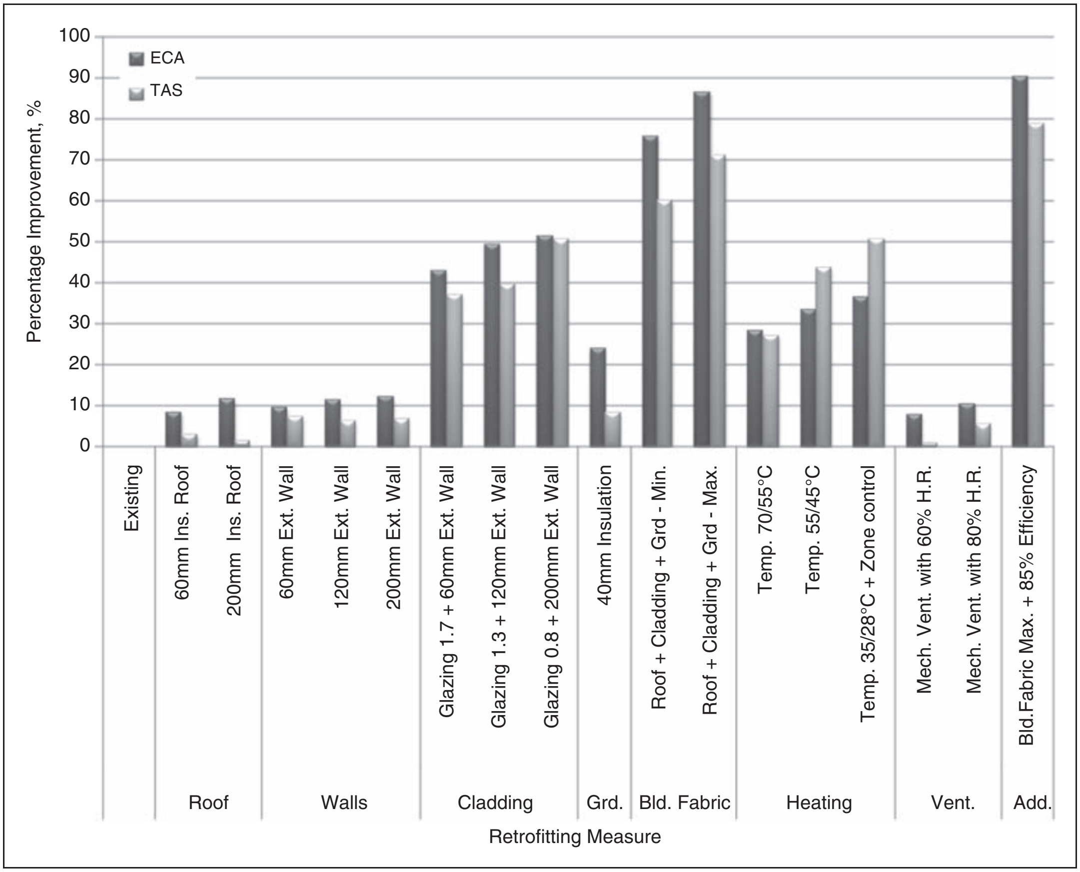

Figure 8. Building B: Percentage reduction in the heating load per retrofit measure

systematic over prediction of potential energy savings: the average difference for both buildings being in the region of 10% (Figures 6 and 7).

Differences in heat ground loss predictions between TAS and ECA are probably influenced by the geometry of the school buildings and perimeter to area ratio (p_f/A_{fg}). ECA generates this ratio based on the inputted areas and volume. For example, a back of the envelope calculation give the actual p_f/A_{fg} ratio of 0.14 for Building B, but ECA generated ratio was 0.42. This highlights that inaccuracies arising from limited number of input parameters and representation of the geometry in ECA leads to discrepancies in model predictions. In Building A, which follows a rectangular form, this effect was less significant.

Using the available statistics on total number of schools and floor space in each category, a simple extrapolation was applied to roughly quantify potential for carbon emission reduction of the school building stock in England and Wales. Classification of school building stock by age/type[10] shows that approximately 13% of the existing school estate could be roughly represented by Building A (assuming that all schools in this group are of similar thermal performance). Building B is representative of 26% of school building stock (1945-1966), and is seen to have thermal characteristic similarities with other schools built in the 1967-1976 period (23% of the school building stock). Therefore, it is representative of 49% of the school building

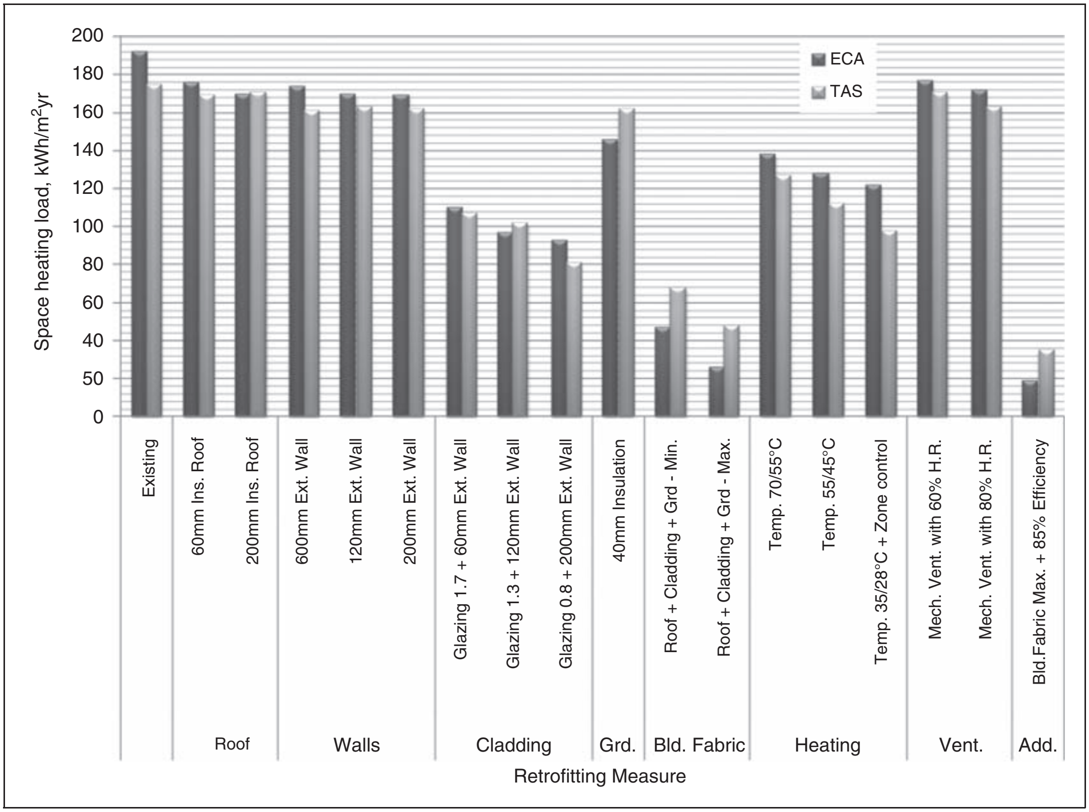

Figure 9. Building B: Space heating load per retrofit measure in kWh/m^2/yr

stock. It is assumed that post 1976 school buildings (24% of the existing school estate) were designed with better thermal characteristics.

Based on the pre and post retrofit modelling results, the emissions due to space heating loads were reduced by 78% and 79% for Building A and Building B, respectively. Water heating, lighting and equipment loads were not included in the simulation, therefore these energy loads and respective carbon emissions were extracted from the energy bills provided by the school. An overall reduction of 53% and 51% was therefore obtained for Building A and Building B by applying conversion factors of 0.422 and 0.194 kgCO$_2$/kWh for electricity and gas, respectively.

In absence of detailed information regarding the remaining 38% of the schools (9 interwar, 24% post 1976 and 5% temporary), it was assumed that these are responsible for the same emissions as Building B and no reduction in CO$_2$ emissions was considered.

By taking the stated assumptions and using simulation results, a carbon reduction of 31% could be easily achieved by applying conventional retrofit measures presented in Table 2. Furthermore, although this paper does not tackle the financial benefits, it is clear that the discussed retrofitting measures would have a significant impact on the annual spend on energy. Savings are however to be assessed against capital costs and spatial requirements especially when considering retrofit measures such as mechanical ventilation in schools that at present rely on a natural system.

Conclusion

Based on both, the online questionnaire and detailed interviews with selected engineers, in general, the delivery of low carbon building refurbishment is considered possible, but the study indicates that currently there is a lack of (a) adequate awareness regarding the emerging technologies available for low carbon school retrofit commercially, (b) reliable database of recently refurbished schools at present that would provide this type of information and (c) recent good engineering practice guides.

Based on a case study approach, this paper analyses strengths and limitations of available design tools of various complexity: ECA and TAS. Unlike TAS, ECA is not well-established in the UK. The tested software packages were characterised by differences such as (a) time resolution, (b) details of building data, (c) physical effects calculated. Despite this, the study showed that if the simulation is limited to well-defined applications, valid results can be obtained even with relatively simple models such as ECA. Although lack of transparency related to embedded algorithms, especially in commercial tools, is a major problem, the study has highlighted that ECA systematically over-predicts potential for energy savings in school buildings between 10% and 15% in average.

Although less sophisticated, ECA meets its aim of offering designers, architects and decision makers the opportunity of assessing the performance of a particular building and comparing possible retrofitting measures. This makes it suitable for preliminary checks, which assist decision makers primarily at feasibility stage as indications regarding the potential savings from the refurbishment projects can be obtained.

The fact that the software package is easy to use and requires basic knowledge of the building construction and envisaged use may encourage decision makers to invest time in assessing different retrofitting scenarios to accommodate valid solutions in a given budget. Its straightforwardness however also comes with a number of limitations that can lead to imprecise results, which could be rectified by dynamic thermal simulation modelling enabling to make adjustment for occupant behaviour and assess overheating in school buildings. TAS on the other hand requires a greater effort to run possibly making it a too complex tool to use at early stages in a project; however, its more detailed and reliable results make it a suitable tool when looking closer into the thermal behaviour of a building and when studying construction details at design stage.

Since the selected case studies are representative of two typical school types in England and Wales, potential reductions calculated for these two buildings are also applicable to other similar schools. Therefore, the carbon emissions of the school building stock can be reduced by 31% by applying traditional retrofit measures. It has to be noted that this is a very rough estimate only and should not be used to form any policy on refurbishment of school building stock in England in Wales (detailed estimates will be presented elsewhere).

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References

1. DCSF. *Carbon management strategy for schools*, Second Consultation Paper, Department of Children Schools and Families, London, UK, 2009.
2. Prodromou A, Dasgupta A, Jaffar B, et al. Consultation on the school carbon management plan: UCL Evidence, University College London (available online: CIBSE Knowledge Bank, Consultation Papers), 2009.
3. DTI. Energy White Paper: Creating a Low Carbon Economy. Department of Trade and Industry, The Stationery Office, London, UK, 2003.
4. DECC. Climate Change Act, Department of Energy and Climate Change, London, UK, 2008.

5. Wilson A. Refurbishment and climate change. carbon effective refurbishment. *Modern Building Services* 2009; 6(1): 17–18.
6. Mumovic D, Palmer J, Davies M, et al. Winter indoor air quality, thermal comfort and acoustic performance of newly built schools in England. *Building Environ* 2009; 44(7): 1466–1477.
7. Norbäck D and Nordström K. Sick building syndrome in relation to air exchange rate, carbon dioxide, room temperature and relative air humidity in university computer classrooms: an experimental study. *Int Arch Occup Environ Health* 2008; 82(1): 21–30.
8. Bakó-Biró Zs, Kochar N, Clements-Croome DJ, et al. Ventilation rates in schools and learning performance. In: *Proceedings of CLIMA 2007-WellBeing Indoors*, The 9th REHVA World Congress, Helsinki, Finland, 10–14 June 2007, pp.1434–1440.
9. DCLG. Building energy calculation software approval scheme, Department for Communities and Local Government, London, UK, 2010.
10. Nicholson R. A roadmap to zero carbon school buildings. Zero Carbon Task Force Symposium, London, UK, 2009.
11. Camden Council. Dartmouth Park conservation area appraisal and management strategy, London, UK, 2008.
12. Curtis L. *Energy efficient refurbishment of schools*. MSc Dissertation, UCL, London, UK, 2010.
13. English Heritage. Refurbishing historic school buildings. English Heritage, London, UK, 2010.
14. Caruana-Smith. On use of architectural tools for energy efficient retrofitting of schools. MSc Dissertation, UCL, London, UK, 2010.
15. IEA. Calculation tools for the energy concept adviser, International Energy Agency, Annex 36 Task Group Reports, 2010.