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Alternatives to air-conditioning: policies, design, technologies, behaviours

EDITORIAL

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BRIAN FORD
DEJAN MUMOVIC
RAJAN RAWAL

*Author affiliations can be found in the back matter of this article

HIGHLIGHTS

Far from being a panacea, air-conditioning is shown to create social, environmental and economic problems. Alternatives to air-conditioning are identified as a key means of reducing energy demand and carbon emissions, improving resilience to heat, and providing a healthy indoor environment. These alternatives are more than a technological issue and help to reframe coolth as an attribute and not a commodity. This editorial introduces the themes and individual papers in this special issue. It explores the implications of these alternative solutions across a range of issues: health and wellbeing; air quality; heat stress; technical/design solutions; economics and equity; climate change; social expectations and practices; policy and regulation; supply chain and procurement; education and training. Recommendations for change involve policy and regulation, construction industry business models, redefining the design decision process, improving performance and feedback, and updating workforce skills and capabilities.

CORRESPONDING AUTHOR:

Brian Ford

Department of Architecture & Built Environment, University of Nottingham, Nottingham, UK

brianford@btinternet.com

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1. BACKGROUND

Global cooling energy use in buildings has tripled since 1990 (IEA 2020), led by a combination of warmer temperatures and increased demand. Without significant intervention demand for air-conditioning (AC) is projected to rise by 700% by 2050. The most rapid growth in demand for cooling in buildings is taking place in India, China and the US, but the implications of an unsustainable increase in cooling demand are being recognised in many countries around the world. In 2020, China and India introduced national cooling plans: China pledged to increase the efficiency of AC units by 30% by 2030, and India also emphasises the importance of increased energy efficiency and refrigerant transition. The European Union's *Strategy on Heating & Cooling* (2016) calls for specific sustainable heating and cooling strategies to be developed at a national level, which was followed by the French initiative of the 'Biarritz Pledge for Fast Action on Efficient Cooling' at the G7 meeting in 2019.[1] This pledge aims to transform the global *cooling* sector and lower emissions by coordinating efforts to improve the energy efficiency of AC and other cooling equipment, in parallel to the phase down of hydrofluorocarbons (HFCs).

While increased energy efficiency of AC technologies has a significant role to play, continued rising demand will remain unsustainable. In Europe and the US, peak load demand for AC threatens to disrupt power supply, but in India, China and South America power supply disruption is already a regular occurrence. While renewables are making an impact, many countries are forced into continued reliance on coal-fired generation to meet peak demand. Alternatives to conventional AC are urgently needed to reduce peak load demand for electricity, reduce the need for fossil fuel back-up, increase resilience and reduce carbon emissions. But these alternatives embrace much more than a technological issue: they require holistic design thinking, and include social aspects (expectations, behaviours, practices) which may challenge the ways in which work, leisure and other activities are pursued.

This special issue, as set out in the call for papers, explores alternative approaches to providing thermal comfort and ventilation in different climatic zones across the world at the scales of buildings, the neighbourhood and the city. It considers the implications of these alternatives across a range of issues: health, wellbeing, air quality and heat stress; technical/design solutions; social expectations and practices; climate change; policy and regulation; supply chain and procurement; education and training.

A total of 37 abstracts were submitted to the special issue. This led to the publication of 13 peer-reviewed papers (Table 1).

Table 1: Articles in the special issue 'Alternatives to Air-Conditioning: Policies, Design, Technologies, Behaviours', *Buildings & Cities* (2022), 3(1); guest editors Brian Ford, Dejan Mumovic & Rajan Rawal.

AUTHORS	TITLE	DOI
B. Ford, D. Mumovic & R. Rawal	Alternatives to air-conditioning: policies, design, technologies, behaviours (Editorial)	https://doi.org/10.5334/bc.256
H. Schoenefeldt	Technological transitions in climate control: lessons from the House of Lords	https://doi.org/10.5334/bc.161
N. Murtagh, S. Badi, Y. Shi, S. Wei & W. Yu	Living with air-conditioning: experiences in Dubai, Chongqing and London	https://doi.org/10.5334/bc.147
R. Hitchings	Understanding air-conditioned lives: qualitative insights from Doha	https://doi.org/10.5334/bc.155
M. Luo, H. Zhang, Z. Wang, E. Arens, W. Chen, F. S. Bauman & P. Raftery	Ceiling-fan-integrated air-conditioning: thermal comfort evaluations	https://doi.org/10.5334/bc.137
E. Bellas & D. Lucina	Outdoor $PM_{2.5}$ air filtration: optimising indoor air quality and energy	https://doi.org/10.5334/bc.153
P. Drury, S. Watson & K. Lomas	Summertime overheating in UK homes: is there a safe haven?	https://doi.org/10.5334/bc.152
D. Grassie, Y. Schwartz, P. Symonds, I. Korolija, A. Mavrogianni & D. Mumovic	Energy retrofit and passive cooling: overheating and air quality in primary schools	https://doi.org/10.5334/bc.159

(Contd.)

AUTHORS	TITLE	DOI
M. J. Cook, Y. Shukla, R. Rawal, C. Angelopoulos, L. Caruggi-de-Faria, D. Loveday, E. Spentzou & J. Patel	Integrating low energy cooling and ventilation strategies in Indian residences	https://doi.org/10.5334/bc.197
T. de Toldi, S. Craig & L. Sushama	Internal thermal mass for passive cooling and ventilation: adaptive comfort limits, ideal quantities, embodied carbon	https://doi.org/10.5334/bc.156
V. L. Goncalves, V. Costanzo, K. Fabbri & T. Rakha	Overheating assessment in Passivhaus dwellings: the influence of prediction tools	https://doi.org/10.5334/bc.151
L. Thomas, A. Woods, R. Powles, P. Kalali & S. Wilkinson	Comfort, behaviour and energy: geothermal air-conditioning in a residential development	https://doi.org/10.5334/bc.172
C. A. Short, A. W. Woods, L. Drumright, R. Zia & N. Mingotti	An alternative approach to delivering safe, sustainable surgical theatre environments	https://doi.org/10.5334/bc.154
H. Byrd, S. Matthewman & E. Rasheed	Air-conditioning in New Zealand: power and policy	https://doi.org/10.5334/bc.143

2. DRIVERS OF GROWTH IN COOLING DEMAND AND OPPORTUNITIES FOR ALTERNATIVES

Growth in cooling demand in buildings is led by people's expectations and aspirations, moderated by what they can afford. Cooling is typically regarded as a commodity. The market focuses on 'business as usual' and growth, whilst neglecting the urgency to reduce carbon emissions and energy demand. Few people think about the opportunities of obtaining improved performance from existing buildings. Therefore, cooling demand is fundamentally influenced by the location and characteristics of buildings and related cooling systems, but the outcome is not entirely a technological issue. This is evidenced by several papers in this special issue that explore alternative ways to achieve thermal comfort and reduce the dependency on AC.

What are some of the drivers of growth in cooling demand?

2.1 HEALTH AND WELLBEING

Heat stress arising from raised indoor temperatures is becoming a more common experience even in more Northern temperate climates. This can affect the ability to sleep at night (see Drury *et al.* in this issue), and with the increasing incidence of extremes has been associated with excess deaths, particularly among the elderly and very young. The extreme high temperatures of the summer of 2003 were associated with up to 70,000 excess deaths across Europe (Mitchell 2016). Air pollution is also a major issue in many cities, mainly from petrol/diesel engines, but there is increasing concern about pollution from wildfires, leading to pressure to filter fine particulates (see Bellas and Lucina in this issue). This work is highly important as the recent assessment of potential changes to mortality from the implementation of advanced building control systems that measure and predict $PM_{2.5}$ concentrations indoors has demonstrated that the joint control of home air purifiers and window operation based on indoor and outdoor environmental conditions is one control mechanism that has the potential not only to maintain thermal comfort but also to achieve effective $PM_{2.5}$ removal, which, consequently, can lead to considerable health benefits at a relatively low extra energy cost (Wang *et al.* 2022).

The Covid-19 pandemic also has had a huge impact in raising awareness about the importance of ventilation on health and wellbeing, and the need to safeguard against Covid and future pandemics. It has become apparent that recirculation of air may no longer be acceptable, and that 100% fresh air will be desirable in many situations. Early in the pandemic, the World Health Organisation established the WHO Environment and Engineering Control Expert Advisory Panel (ECAP) for COVID-19 to review the available scientific evidence and practices and update recommendations on environment and engineering controls. The WHO (2021) report proposed a roadmap to improve and ensure good indoor ventilation in the context of Covid-19. The Chartered Institution of Building Services Engineers (CIBSE) published a series of documents on Covid-related issues covering ventilation, air cleaning technologies (including the relative exposure index calculator) and safely reoccupying buildings.[2] This was partially based on the latest guidance from the UK's Scientific Advisory Group for Emergencies (SAGE) (2020). However, it may be too early to properly review the implications of the pandemic for ventilation and cooling strategies. No abstracts addressing these issues were received for this issue and this gap needs to be filled.

2.2 THERMAL COMFORT AND THE AGENCY OF BUILDING OCCUPANTS

The social/environmental determinants of comfort expectations, and inhabitants' level of agency clearly have a significant influence on the experience and energy implications of both living with and without AC. These drivers are addressed by several papers (see Murtagh *et al.* and Hitchings in this issue). The findings confirm that in many circumstances thermal comfort is a negotiated condition. A loss of agency by inhabitants yields resentment and a reduction in acceptable thermal comfort. This suggests opportunities for improvement in facilities management, and potential for increasing individual agency with personalised solutions.

2.3 CLIMATE CHANGE

Overheating in buildings will be exacerbated due to both increasing extreme weather events and the gradual increase in average summer temperatures. By 2100, cities across the world could warm as much as 4°C on average (Zhao *et al.* 2021)—more than double the Paris Agreement's goal of limiting global temperature rise to no more than 1.5°C. In many countries improved insulation standards introduced to reduce winter heat losses may increase the risk of summer overheating. The incorporation of elements with high thermal capacitance can help to stabilise internal temperatures (see de Toldi *et al.* in this issue), and where this is coupled to night-time ventilation in summer, can pre-cool the interior for the following day. In warmer climates, where night-time temperatures remain high, other natural heat sinks may be applied to reduce the need/demand for cooling. Mapping the applicability of different passive cooling techniques in different parts of the world will be of benefit to building designers. Unfortunately, local standards and analytic tools often assume an engineered, tightly controlled environment as the default to be achieved. With reduced reliance on mechanical ventilation and cooling, the wider adoption of adaptive thermal comfort criteria should be encouraged.

2.4. ENERGY USE AND ENVIRONMENTAL IMPACT

AC was responsible for 1 Gt CO_2 emissions in 2019 (8.5% of total annual electrical consumption globally) (IEA 2020). While this is relatively small on an annual basis, AC can represent 60% of the peak load. Peak demand for electricity is now associated with AC in most cities worldwide, dumping hot air into already overheating city streets, and increasingly outstripping supply (the cause of recent power-outages in Beijing in 2018 and New York in 2019). More efficient AC is not the (only) solution. Simple, effective, robust measures designed to reduce cooling load will have an impact very quickly and reduce peak load. Planning for intermittency of energy supply is an increasingly vital consideration for resilience to ensure that thermal adequacy can be provided without a dependency on AC. Planning for urban heat islands (UHI) remains difficult to predict in the changing climate due to the simultaneous reduction in heating and the increase in cooling demand resulting in less effective passive design strategies and posing a significant risk to human health and biodiversity. These are challenges not just for the building professions but also for city authorities and major property owners globally.

2.5 ECONOMICS AND EQUITY

Of the 35% of the world's population living in countries where the average daily temperature is above 25°C, only 10% own an AC unit, but increasing affluence is supporting rapid increasing demand, which has tripled globally since 1990. In India and other Southeast Asian countries, increasing affluence is resulting in rapid expansion in demand for residential AC units, but the alternatives should be encouraged by local and national governments. Cook *et al.* present positive results for a 'mixed-mode' approach to residential cooling in India. In many African states, communities facing major financial challenges will often not even consider conventional AC.

However, there are encouraging examples of the application of alternative approaches, such as the excellent schools provided at low cost in Burkina Faso by Francis Kere Architecture, and the work by Nina Maritz Architects in Namibia, who apply a wholly passive design approach to address cooling needs.

Equally, it is in the interests of the commercial sector to make improvements to poor workplace environments. Poor workplace environments impact the productivity (and health and wellbeing) of workers, which can be remedied by promoting a combination of 'best practice' and improved standards (Hossain 2020).

When viewed through the lens of climate justice (Klinsky & Mavrogianni 2020), it is apparent that while a passive design approach to cooling in buildings is highly relevant in most circumstances, a comprehensive review of the implications for the most vulnerable (socially, economically and environmentally) is required. The thermal resilience of communities under extreme conditions has been examined by Hamstead *et al.* (2020) and Passe *et al.* (2020), and is explored in relation to adaptive opportunities for residents in UK housing and the need to identify 'safe havens' by Drury *et al.*

2.6 THERMAL CHARACTERISTICS OF BUILDINGS AND CITIES

Conventional AC systems exacerbate UHI effects, dumping heat into city streets at the hottest time of the year. Policies and design approaches to minimise UHI effects are being actioned. City authorities are engaging with this issue (*e.g.* the Million roofs challenge), but much more needs to be done in urban design and planning to harness relevant local conditions (wind patterns for cooling, massing and shading of buildings, afforestation, green and blue urban infrastructure, *etc.*). Most of the buildings standing in 2050 already exist in mature economies: retaining, adapting and reusing existing buildings must become the norm. This will present significant design challenges for zero-carbon refurbishment to avoid or minimise the need for mechanical cooling. Zero-carbon workshops for early-career professionals could involve collaborations between city authorities, professional groups and universities, and are being promoted internationally by the Global Cool Cities Alliance (2022).

2.7 SOCIAL EXPECTATIONS AND DEMOGRAPHICS

There is a compelling need to deliver thermal adequacy for an increasingly urban world. Within the UN's Sustainable Energy for All Programme (2018), the global panel on access to cooling has produced a report exploring the wide-ranging challenges for people without access to cooling. It quantifies the access gaps in key regions and countries for the first time. It also offers advice and guidance to policymakers on how to measure the gaps in their own countries and how to think more systematically about pathways that bring sustainable cooling to populations that rely on them for food security, health and productivity.

2.8 DESIGN AND INNOVATION

More efficient AC is often posed as the solution, but it has been shown in many circumstances we can 'design-out' the need for AC (*e.g.* Francis Kere's schools in Burkina Faso), or significantly reduce the need. Natural heat sinks have a significant part to play, and economic as well as environmental feasibility is being demonstrated by an increasing number of high-quality buildings that adopt passive design principles (*e.g.* much of the recent work by Morphogenesis Architects, Delhi). Radical improvement in AC performance also has its part to play (Sachar *et al.* 2018).

3. CONTRIBUTIONS IN THIS SPECIAL ISSUE

Concern about the negative environmental impact of mechanical refrigeration and cooling technologies has led to a re-examination of the quality of the internal environment in buildings before the development of mechanical conditioning. Prior to the 19th century, the quality of the internal environment was largely determined by design: the building form and fabric, plan and section, the disposition of openings and the relationship between them. This has been referred to as 'passive' or 'structural' environmental control, and was considered to be an integral part of architecture. The invention and development of AC enabled environmental control to be treated as a problem of mechanical engineering rather than a function of architecture. However, it was during the early 19th century that a hybrid approach to environmental control evolved combining passive/structural measures with early mechanical devices to deliver environmental control within large public buildings. *Schoenfeld* illustrates this when he describes the design and performance in use of the House of Lords chamber in the UK Parliament, which he describes as a 'transitional technology between the structural and mechanical eras'.

Through a detailed examination of the environmental performance of the House of Lords chamber, over 112 years of its operational history, it has been established that the design and operation was, in large measure, satisfactory when judged against contemporary CIBSE standards. The paper also illustrates what is described as an 'alternative facilities management model' based on occupant experience and feedback. Operation of the House of Lords included the use of sensors and mechanical controls, but most importantly included continuous feedback from the occupants to the operational staff. This is significant in the current context: today's mechanically conditioned environments are widely regarded as reducing user autonomy, but greater user involvement in their environment would align with adaptive comfort theory and practices.

It is interesting to compare this extraordinary account of the operational history of the House of Lords in London with the detailed examination of occupant experience in two further papers in this special issue which focus on the experience of living with AC in different parts of the world.

Murtagh *et al.* report on 'experiences of living with and without air-conditioning', based on interviews with people living in Dubai, Chongqing and London. This paper reviews recent studies of occupant behaviour in different parts of the world, which have mostly been related to the experiences of older people. In contrast, this investigation focused on the experiences of a mix of working-age respondents in each city.

In London, where AC was not installed in any of the respondents' residences, participants showed a range of behavioural adaptations to heat, with negligible impact on social interaction or health. However, in Dubai and Chongqing where AC is ubiquitous, residents reported doing less exercise, having social interaction and suffering a number of health issues. While they also recognised that AC enables indoor work to proceed under extreme outdoor conditions, most respondents in these cities also reported 'overcooling' as a significant issue. Although respondents in Dubai and Chongqing recognise their dependence on AC, and their adaptation to very cold internal temperatures in summer, people do not experience AC as providing a comfortable environment. They also regard the AC environment as unhealthy, with poor indoor air quality. The authors conclude that the idea that AC is the unique solution to extreme heat must be challenged, and that 'behavioural, social, built environment and other technical solutions' should be evaluated in developing a comprehensive approach to heat stress.

These conclusions are supported by the findings of *Hitchings* who reports on a survey of (relatively affluent) residents in Doha, Qatar. Their findings support those of the previous paper that AC can create rather than respond to local preferences and expectations, and that a perception of 'over-cooling' is commonplace. The development of AC in the early part of the 20th century was associated with affluence and status, and this has continued to be the case to the extent that over-cooling is regarded (by some) as desirable, and has become normalised. This will be familiar to many in different parts of the world where 'winter' clothing is often worn as an 'adaptive' response to over-cooled buildings (Derrible & Reeder 2015). This is further illustrated by the story of an academic in New York who complained about 'over-cooling' in her office and was provided with a heater by the facilities manager. While the culture of fossil fuel profligacy must be challenged, it may also be the case that individual 'tailoring' of our thermal environments and personal control systems may be valid and indeed promote energy efficiency (Tang *et al.* 2022).

Such localised 'tailoring' may potentially be also provided by ceiling-fan-integrated air-conditioning (CFIAC), which is the subject of *Luo et al.* CFIAC systems address the problem of energy consumption by air terminal supply ducts and diffusers and the delivery of air uniformly in the space by conventional heating, ventilation and air-conditioning (HVAC) systems. CFIAC is a way to eliminate ceiling-mounted ductwork and use ceiling fans to distribute mixed air into the room. With CFIAC, air supply terminals and ceiling fans would be coordinated to work either in a synchronised manner or separately in different operational modes. This study evaluates the thermal comfort performance of CFIAC systems under various ambient temperatures and fan operation modes by human subject experiments and thermal manikin tests across the room's floorplate.

The study demonstrates that in the presence of CFIAC operating at 28°C, the comfort conditions were similar to comfort conditions achieved by overhead air supply at 26°C. In cooler environments, the upward-directed fan can prevent the sensation of overcooling. The study also concludes that standard effective temperature (SET) can predict the cooling effects of the elevated airspeeds and temperature distributions produced by high-side-wall vent supplying ceiling fans, and be a useful thermal comfort evaluation tool for CFIAC systems.

In many cities in different parts of the world external air quality is extremely poor and filtration of external air may be important to provide a satisfactory (healthy) internal environment. However, filtration of fine particulates can further increase energy use. *Bellas and Lucina* suggest that building designers should consider a dynamic variation of local outdoor $PM_{2.5}$ when selecting the outdoor air filtration in order to reduce energy demand from the mechanical ventilation fans without compromising indoor air quality. Currently, the $PM_{2.5}$ filter selection recommended by the standards is based on the annual average outdoor concentrations without considering seasonal or diurnal fluctuations. This could result in a waste of energy or elevated indoor $PM_{2.5}$ exposures. With human inhalation exposure to fine particulate matter ($PM_{2.5}$), including the $PM_{2.5}$ of outdoor origin, predominantly occurring indoors, this issue is becoming increasingly important. However, this study has found that outdoor air is over-filtered in the majority of the 37 investigated cities. In cities with low-to-moderate outdoor $PM_{2.5}$ levels, using a filter bypass can be an effective energy conservation method without compromising $PM_{2.5}$ exposures indoors, on average from 4% to 14%.

Poor air quality in cities worldwide suggests that such savings are certainly worth achieving during the transition to a global clean-tech economy. The improvement of existing cooling systems and existing buildings must form part of any strategy to reduce cooling energy demand.

It is a paradox that in temperate climates, measures taken to reduce heat loss in winter are likely to increase the risk of overheating (and demand for AC) in summer. In Europe improvements in the thermal performance of the building envelope has been mandated by the European Union's Energy Performance in Buildings Directive (EPBD), and revised a number of times since its introduction in 2003. This has been successful in significantly reducing energy consumption of typical buildings, and the most recent revision (December 2021) targets existing buildings in particular, with the ambition to achieve a zero-emission and fully decarbonised building stock by 2050. While radically reducing heating demand, summer cooling demand is on the rise and some studies have suggested almost as much energy would be needed for cooling as for heating by the middle of this century. In the UK, energy use for AC and cooling is approximately 10% of total electrical energy use (Abela *et al.* 2016). However, it is evident that passive measures combined with the creative adaptation of existing buildings will be required if wider adoption of AC is to be avoided.

The creative adaptation of UK housing to provide 'safe havens' during heatwaves forms part of a study of overheating risk and adaptive opportunities in UK homes reported by Drury *et al*. This suggests 'safe havens' may provide an alternative to installing AC. The study is based on measurements of temperatures in bedrooms and living rooms of a large sample of existing UK housing, across a range of house types, during the unusually hot summer of 2018. It also projected summertime thermal performance forward to 2050 and found that safe havens may exist in 76% of the existing housing stock. While this may exceed the proportion of homes in which this can be achieved in practice, policies to promote the use of safe havens during heatwaves could be effective if targeted at particular house types (detached and semi-detached in the UK) and those most vulnerable to the health risks of overheating. Other (passive) adaptive measures were found to be highly effective in combatting high summer night-time temperatures in the UK.

English school children spend approximately one-third of their waking hours in classrooms. They are more vulnerable to the impacts of higher indoor temperatures and lower quality of indoor air than adults. Grassie *et al.* investigated 111 archetypes of English naturally ventilated classrooms for their overheating risk and air quality using building modelling and simulation methodology. A unique air flow network (AFN) modelling was used to model the thermal and environmental qualities of school building classroom stock. Key aspects are indoor temperatures, heating demand, concentration of indoor CO_2, NO_2 and $PM_{2.5}$, and geographical location (*e.g.* terrain, orientation and levels of outdoor pollutants). Increased ventilation could lead to the possibility of ingress external pollutants in urban areas. The study identifies the most vulnerable classrooms and highlights a range of retrofit and passive cooling measures. However, even with these measures, future climate scenarios indicate that a high level of overheating for some building types and locations will occur, and mechanical cooling and air filtration systems are likely to be needed by 2080.

Opportunities for reducing cooling energy demand in Indian residential buildings have been identified through a mixed-mode approach by *Cook et al.* This paper presents an analysis of natural ventilation/mixed-mode cooling of residential buildings in four cities in India. It compares a 'business as usual' approach (full mechanical AC) with enhanced natural ventilation with appropriately sized windows and controls (LECaVIR). The results suggest that the LECaVIR approach can potentially achieve significant reductions in the number of mechanical cooling hours (40–55%) relative to full AC across the four main climates of India. In the context of rapid urbanisation and the projected significant growth in demand for improved thermal performance in new housing, these findings are very relevant to practice and to policymakers, not only in India but potentially in similar climates in other parts of the world.

It is important to find alternatives to standard AC systems that take into account both embodied and operational emissions. The use of passive cooling during heatwaves in Canada is examined by de Toldi *et al.* in terms of adaptive comfort limits, ideal quantities of thermal mass and embodied carbon. This paper argues that the internal thermal mass of a building coupled with buoyancy ventilation can significantly reduce the need for active AC and in turn mitigate climate change. The results of the paper conclude that thermal mass would provide comfort considering adaptive thermal comfort theory against heatwaves in Canada without mechanical cooling. It also quantified per person quantities of thermal mass required. The paper discusses the life-cycle carbon emissions associated with building materials that will provide thermal mass. Thermal mass for passive cooling can play a significant role within the design of hybrid cooling approaches and can contribute to a reduction of the operating hours of active systems.

With overheating becoming a major issue in Europe, the prediction of the indoor thermal performance by using dynamic building simulations became common practice by researchers and practitioners. Performance simulation of housing can be fraught with difficulty, particularly with regard to air-flow modelling. Goncalves *et al.* investigate the effect of simplifications commonly made in airflow modelling techniques on the overheating assessment of passive houses by using measured data and calibrating a thermal model with a passive house case study. The study found that the difference in the results between the Building Energy Modelling (BEM) and the AFN and computational fluid dynamics (CFD) model on indoor temperature and overheating hours follows a decreasing tendency as the outdoor temperature decreases. It demonstrated that the specification of air-change rates from which the flow rates are calculated based on the volume of the room does not represent the realistic airflow in buildings unless located in a colder climate where the role of natural ventilation is diminished. Both the orientation of the window openings with respect to the wind direction and the existence of wind-blocking elements around the studied building, which determine the pressure difference and hence the airflow rate, are neglected when using the thermal model alone. The large difference in the number of overheating hours emphasises the need for a more detailed analysis of the airflow in building simulations.

With changing climate and increasing number of warm days, Thomas *et al.* focus on thermal comfort expectations and preferences in residential buildings in Sydney, Australia. This detailed study of 40 homes with integrated geothermal AC (ground-source heat pump air-conditioning—GSHP-AC) covers one of worst (hottest) summers in recorded history and increased daytime occupancy over winter through work from home during Covid-19 lockdowns. The 'conditioned expectations' and preferences of some occupants were for a narrower band of temperatures while heating or cooling is deployed. A vicious cycle of expectation or critical dependency on AC influences a lower tolerance of 'imperfect' conditions, and vice versa. This can increase GSHP-AC energy and squander much of the savings that could be realised through increased utilisation prompted by the availability of heating and cooling on stand-by. The replacement of conventional AC with efficient alternate technologies is not a one-stop solution.

It is clear that the expectations of users must be accounted for when marketing new energy-efficient technologies, as user engagement and understanding is required if potential energy savings are to be achieved in practice. User expectations in residential buildings will of course be different from those in hospital buildings, although the search for low carbon alternatives to AC is equally important.

Short *et al.* examine the ultra-clean ventilation (UCV) spaces required for surgical environments. The design intent of traditional UCV systems was to divert airborne pathogens from a surgical wound by driving pre-cooled air downwards onto the patient before extraction at a high level. Over 5% of patients undergoing surgery in the UK develop a surgical site infection (SSI)—so this is a significant clinical and health issue. This study suggests that an alternative up-flow displacement ventilation scheme could provide a safe and well-ventilated interior space in which the air flow can be driven by buoyancy and wind forces. It is proposed that high-efficiency particulate air (HEPA)-filtered air is passed directly onto the wound site and instruments as directed by the surgical team, rather than saturating the whole space with HEPA-filtered air. This new approach offers a less complex solution with less mechanical servicing, fewer scarce components, lower maintenance commitments, lower energy requirements and operating costs than current UCV environments. It is hoped this will lead to prototyping and full-scale evaluation.

The final paper in this special issue considers the role of policy measures driven by codes, standards and a voluntary assessment programme that has impacted the cooling demand of buildings in New Zealand. Byrd *et al.* consider the glazing within a facade. A double-skinned facade for a highly glazed and AC building attempts to mitigate a problem that could be solved with a significantly lower proportion of glazing. The paper argues that the voluntary programme has no criteria for performance assessment based on the actual operation of buildings. In the light of this, a new tool to measure the energy performance of a building has been developed by the New Zealand Green Building Council to support the policy's definition of a 'green building'. The paper argues that with the availability of these tools and standards, a larger proportion of commercial buildings need to be evaluated for energy use and cooling load, and that the reasons behind policy paralysis need to be discussed in order to curtail the use of over AC. New Zealand's building energy efficiency standards have not changed in a quarter of a century and existing energy efficiency legislation allows buildings to be designed without accounting for cooling loads.

Sadly, this lack of regulation with regard to the provision of cooling in buildings is common in many parts of the world. But should the focus actually be on the achievement of thermal comfort (rather than reducing cooling demand), and on the potential benefits for building occupants and those who fund building improvements?

The papers in this special issue describe a wide range of different approaches to 'alternatives to air-conditioning' and contribute to an understanding of the opportunities for better informed practice and policy, while also revealing a number of significant gaps. Some of these gaps and recommendations for change are identified in the next section.

4. RECOMMENDATIONS FOR CHANGE

Ambitious requirements for energy performance in buildings have been fostering innovation in industry to deliver net zero carbon buildings in use. This will require the entire construction and property industries to rethink the way we design, construct, operate and market our buildings. New pathways to successfully implement alternatives to AC need to be led by policy and regulation, as well as new business models in creating market demand. In this transition to a low carbon future the questions are not just 'What?' and 'Why?', but primarily 'How?'.

4.1 POLICIES, REGULATIONS AND INCENTIVES FOR CLIMATE CHANGE

Policy issues are hugely significant in encouraging 'the market' to respond appropriately. Local, regional and national governments in the developed world must encourage new development to focus on the reuse of existing buildings, and only 'allow' new construction when other options have been exhausted. Inventive reuse of buildings will enable huge savings in embodied energy.

Voluntary incentive schemes formed by regulatory or administrative instruments are also one of the possible measures to promote sustainable building design and increase the motivation of developers to meet higher standards. The effectiveness of such schemes will depend on local socio-economic circumstances in each region or nation. A theoretical framework was established to test and explain the effectiveness of concession schemes, and the potential benefits for the developers (Qian *et al.* 2016).

Focusing on alternatives to AC, another way forward is to embed more sustainable cooling techniques (Carbon Trust *et al.* 2021) in regulatory documents including passive cooling (avoiding or reducing the need for mechanical cooling including reductions in cooling loads, smart and human-centric design and urban planning), super-efficient equipment and appliances, and ultra-low global warming potential (GWP) refrigerants.

Unfortunately, alternatives to AC, while widely recognised to be of value, still seem to be treated as 'second best'. Approaches that are unfamiliar to the mainstream may require more initial design time (to allow for testing, evaluation and confidence-building) and in commissioning, where there are always temptations to take short-cuts. Mandating a higher quality of commissioning through regulation is feasible (Lord *et al.* 2016).

4.2 CONSTRUCTION INDUSTRY TRANSFORMATION IN THE CONTEXT OF CLIMATE CHANGE

The construction industry debates how their businesses can become a force for good. The converging view is that the commitment needs to come from the top and be supported from the bottom up. If clients fully buy in to net zero, and the implications and constraints that come with it, that will go a long way to making the aspiration achievable. An increase in global warming significantly increases the risk of drought, floods, extreme heat and climate-related poverty for millions of people across the world, and ethical issues are practical business issues. Understanding that the motivation of building designers is not purely financial, several practices start fostering a sense of purpose when working on building projects that align with their key values.

The time–cost–quality triangle (sometimes referred to as the Golden Triangle) is a common model for describing the constraints, and trade-offs, required to deliver a project in the built environment. Recognition of environmental considerations and the need to reduce carbon emissions is increasingly recognised as a constraint on development and a constraint affecting the ability of teams to deliver projects on time, on budget and of an appropriate quality. The tension between time, cost, quality and carbon affects developments at several levels: the project as a whole as well as on individual building components. At a project level some design teams have developed carbon risk registers to manage the risks and challenges of integrating carbon reduction into construction processes. The status of carbon and its relationship to time cost and quality indicate a need for the Golden Triangle to be revised to a square (Figure 1).

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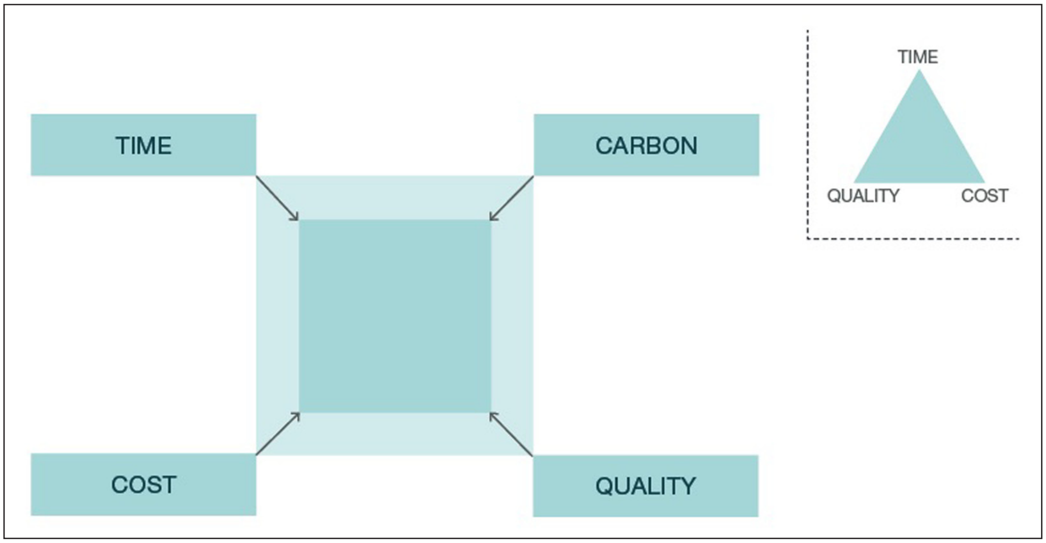

Figure 1: Time–cost–quality–carbon square.

Making this adjustment not only highlights the importance of carbon in development, its relationship with other constraints and the need to manage this aspect of the delivery of a project, but also highlights the temporal nature of the relationship of a development to its carbon emissions. Time, cost, quality and carbon decisions influencing capital expenditure at the outset of a development have long-running implications on the operational expenditure influencing everything from the energy expenditure to the effort required to clean and maintain a building. These design decisions have other long-running effects on aspects of a development such as on the quality of the users' experience of the building and the usable life of a building. Similarly cost, quality and time decisions at the outset of a project have life cycle carbon implications affecting operational energy, patterns of replacement and refurbishment, and the ability to reclaim resources, invested in the building at the beginning of its life and at the end of its life.

4.3 REDEFINING PROFESSIONAL PRACTICES AND DESIGN DECISION PROCESSES

Embedding design alternatives to AC can only be achieved by a collaborative effort from the entire design team. Each discipline has a responsibility to reduce the heating and cooling demand of the building. This entails a more nuanced decision process (compared with net zero) to identify the trade-offs required to reduce the whole life carbon on a live commercial project. This will involve:

- thinking circularly rather than linearly
- thinking beyond individual buildings to how systems (including processes of material production and energy generation and distribution) interact at the nexus point of a new development
- thinking rigorously forwards and backwards in time considering the processes supporting new development, building use and future reuse
- recognising that buildings have a role contributing to broader societal goals and have lives, which mean that they will change and adapt over time.

Is there an approach (design process) that can be adopted by design teams that could lead to reliable delivery of zero-carbon/sustainable buildings? The definition of an environmental design strategy (or options) for a particular building must start with an examination of the context (including climate) before postulating how the building may respond to (existing and future) seasonal and diurnal variations. Having defined strategic options conceptually, they must be evaluated, initially with simplified tools and then with increasing sophistication, to give confidence in the strategy as the design is developed in detail.

4.4 UNDERSTANDING DESIGN PERFORMANCE TOOLS

In the detailed design stage, building energy modelling requires a high level of detail in order to predict the energy use of a building. Myriad parameters with a certain level of uncertainty can influence the final performance due to aggregated effect of uncertainties. CIBSE TM63 (2020) defines the following uncertainties: specification, modelling, numerical, scenario and heuristic. Simplicity should be the aim of the design as many of the underlying issues are related to the complexity of the building systems where performance in use is less understood. For example, mechanical systems and their control systems often do not capture dynamic behaviour and the part-load operation of the mechanical system or the response of feedback control systems. Similarly, in design calculations, occupancy is normally accounted for through a profile that is simplified by taking the average behaviour of the occupants, and therefore neglects variations between personal preferences of people, and different senses of comfort.

A significant variation often exists between simulation tools and actual performance in use. The definition of good modelling practice at the design stage can be found in CIBSE TM54 (2022), to ensure that the calculations are performed in a robust and systematic manner for both the building fabric and building services, and propose results analysis, including scenario testing and sensitivity analysis, to determine the impact of assumptions, design and operational parameters. This yet-to-be-implemented best-practice document provides guidance on reporting and quality checks, but is yet to be implemented and tested in practice.

4.5 REVIEWING PERFORMANCE AND DESIGN FOR PERFORMANCE

Studies of performance in use are vital in confirming the validity of the general direction of travel in the field and evolution of tools and methods to design for performance. While the original RIBA's Plan of Work of 1963 included Stage M—Feedback, it was woefully underused and removed in 1972. The same year, Markus *et al.* (1972) published a pioneering book on building performance. In 2001, *Building Research & Information* published a special issue on post-occupancy evaluation,[3] followed by Bordass's (2003) 'Learning more from our buildings, or just forgetting less?'. In 2014, Roderick Bunn prepared a set of three BSRIA guides: *How to Procure Soft Landings—Specification and Supporting Guidance for Clients, Consultants and Contractors* (Bunn 2014a), *The Soft Landings Core Principles* (Bunn 2014b) and *The Soft Landings Framework—For Better Briefing, Design, Handover and Building Performance In-Use* (Bunn 2014c). The headquarters for Bath and Northeast Somerset Council is the first building in the UK to employ the full 'Soft Landings' methodology, where the energy performance aims were not just forecast in the design but written into the contract setting, a precedent where responsibility for underperformance might be identified. After nearly 60 years, RIBA reinstated post-occupancy evaluation during Stages 6 and 7 of the 2020 RIBA Plan of Work as 'critical to optimising in-use performance'.

In 2014, the first edition of CIBSE TM54 (2022), *Evaluating Operational Energy Performance of Buildings at the Design Stage*, defined a method on how to design for performance. CIBSE TM63 (2020) provides a formal way of linking post-occupancy evaluation studies back to design stage modelling and calibration. It provides a protocol on how to link design stage modelling and post-occupancy evaluation. To understand if alternatives to AC have been implemented successfully, one needs to gather evidence that will provide insights for use on future projects, followed by detailed data analysis to help engineers achieve anticipated design performance, and finally engage facilities managers and users to aid their understanding of the environmental design and building operation.

Optimisation starts before a building is handed over to the users through robust and intensive commissioning to ensure that systems are operating at their optimal performance. This continues beyond practical completion to ensure that environmental systems are correctly interfacing with users and operators. The optimisation period starts with commissioning and ends several years after occupancy to enable user queries to be understood and addressed.

4.6 TIGHTENING CONTINUING PROFESSIONAL DEVELOPMENT FRAMEWORKS

All professions (collectively and individually) have a responsibility to society to ensure their members' knowledge and capabilities are actually able to promote the principles of sustainability and seek to prevent avoidable adverse impacts on the environment and society. Codes of conduct for engineering professions across the globe oblige engineers to 'only undertake work for which they have sufficient professional and technical competence and adequate resources to meet their obligations'. They should also disclose relevant limitations of competence.

For example, the successful implementation of alternatives to AC requires the updating of all individuals' skillsets to ensure a robust workforce can undertake this course of action, especially when the pool of experience is relatively limited. 'The Way Ahead', RIBA's new education and professional development framework, has determined that the core competency for architects must encompass a fundamental level of awareness and understanding of priority subjects for them to be competent to practice and to provide public assurance including climate literacy (to demonstrate their ability to design buildings that deliver sustainable outcomes and meet the RIBA 2030 Climate Challenge), ethical practice (to demonstrate their duties to themselves, to the profession, to those commissioning services, to those in the workplace, to society and the end user, and to the wider world), and research literacy may follow in future. To ensure UK chartered members can provide up-to-date evidence of their competence, it is proposed that they will be reassessed every five years.

The current review of professional competencies required for practising architects in the UK by the Architects Registration Board (ARB) has been described as the biggest change in architectural education for 50 years. The need for these changes has been discussed in a recent special issue of *Buildings & Cities*.[4] All the construction professions need to be on board if the fundamental and rapid improvements in building performance and sustainability are to be achieved in practice.

NOTES

1. Biarritz Pledge for Fast Action on Efficient Cooling. https://www.elysee.fr/admin/upload/default/0001/06/306cf93611abfad315fbc8ebce8e86dc27282363.pdf.
2. See https://www.cibse.org/coronavirus-covid-19/emerging-from-lockdown#1/.
3. See https://www.tandfonline.com/toc/rbri20/29/2/.
4. 'Education and Training: Mainstreaming Zero Carbon'. https://journal-buildingscities.org/collections/special/education-and-training-mainstreaming-zero-carbon/.

AUTHOR AFFILIATIONS

Brian Ford orcid.org/0000-0003-1343-824X
Department of Architecture & Built Environment, University of Nottingham, Nottingham, UK

Dejan Mumovic orcid.org/0000-0002-4914-9004
UCL Institute for Environmental Design and Engineering, The Bartlett Faculty of the Built Environment, University College London, London, UK

Rajan Rawal orcid.org/0000-0001-7914-6069
Centre for Advanced Research in Building Science and Energy (CARBSE), CEPT University, Ahmedabad, Gujarat, IN

COMPETING INTERESTS

The authors have no competing interests to declare.

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