The Bartlett
Institute for Environmental
Design and Engineering (IEDE)

SHAPING THE SUSTAINABLE BUILT ENVIRONMENT IN A CHANGING CLIMATE

Celebrating 60 years of Environmental Design and Engineering at The Bartlett

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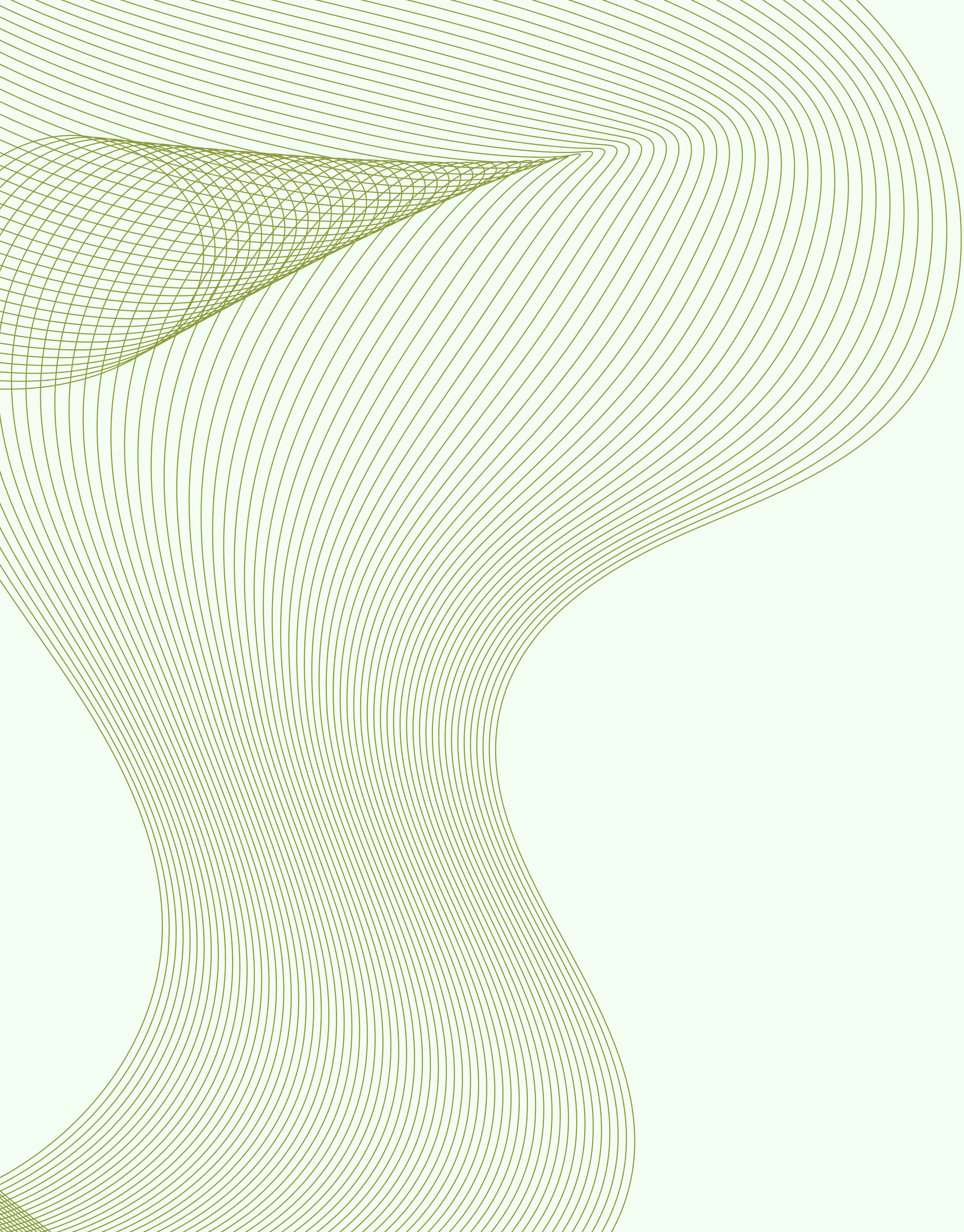


With thanks to Reham Alasmar whose front-cover design submission for the anniversary book competition helped shape our early thinking.

The Institute for Environmental Design and Engineering (IEDE)

We are The Bartlett.

COLLABORATION WITH INDUSTRY

RESEARCH

STAFF

PREFACE

2025 is the year when we mark 60 years of Environmental Design and Engineering (EDE) at The Bartlett, UCL. It is thus an opportune time to take stock of how far we have come. Since Prof. Sir Richard Llewelyn-Davies appointed Ralph Hopkinson as the first Chair in Environmental Design and Engineering in 1965, we have enlarged the scope of architectural engineering research and education to incorporate environmental and human factors. There are three distinctive periods in the development of EDE at The Bartlett: (a) 1965–1991: 'Experimental Revolution'; (b) 1992–2013: 'Growing a Research Powerhouse'; and (c) the current one, 2014–present: 'Revolutionary Evolution'. The detailed review of all three periods is given in the history chapter of this book written by architect Dr Judit Kimpian.

Today, the UCL Institute for Environmental Design and Engineering (UCL IEDE) pursues a deep understanding of the interactions between the built environment and health, human wellbeing, productivity, energy use and climate change. The UCL IEDE is part of The Bartlett's research-intensive School of Environment, Energy and Resources (BSEER), which also facilitates our sister institutes (Energy Institute, Institute for Sustainable Heritage and Institute for Sustainable Resources) by providing strategic leadership and professional services support. In addition to the offices in Central House in the Bloomsbury campus, the UCL IEDE's experimental facilities, launched in 2018, are based at UCL Here East, which houses our light and lighting labs, high-performance environmental chambers (human and material), acoustics and audio facilities, and a building services teaching lab. UCL Here East is a joint venture between The Bartlett Faculty of the Built Environment and the UCL Faculty of Engineering Sciences based at the Queen Elizabeth Olympic Park, East London. This 6,000sqm technology and creative facility is also a home of the UK Centre for Moisture in Buildings.

Currently, the IEDE hosts over 110 academic staff, research associates and doctoral researchers. The Institute is home to approximately 130 students across four postgraduate programmes: Environmental Design and Engineering (1978), Light and Lighting (1987), Health, Wellbeing and Sustainable Buildings (2017), and Smart Buildings and Digital Engineering (2018). Since the UCL IEDE was established in 2014, we have diversified our teaching portfolio by creating two undergraduate programmes. A total of 240 students study on our joint triple-accredited Engineering and Architectural Design MEng (2017), delivered in partnership with The Bartlett School of Architecture, UCL, and UCL Civil, Environmental and Geomatic Engineering. We also recently launched the dual degree Sustainable Built Environments, Energy and Resources BSc/MEng (2022) with our sister institutes within BSEER, linking architectural engineering with resource economics, energy systems and heritage. Currently in its first four-year cycle, this programme is designed to eventually educate approximately 210 students per year.

The total value of the UCL IEDE research portfolio will exceed £25 million in 2025, and we publish five peer-reviewed papers per academic per year on average. The UCL IEDE was also a recipient of three consecutive Engineering and Physical Sciences Research Council (EPSRC) Platform Grants, awarded to "world leading research groups", and we are recognised as a Centre of Excellence in Sustainable Building Design by the Royal Academy of Engineering – one of only four in the UK. The Institute's new strategy calls for research and teaching temporal integration across the spatial scale: from urban to building to human. In 2024, we have defined eight research themes which are also a basis for our research-based teaching pedagogies: (a) Light and Lighting, (b) Acoustics and Soundscapes, (c) Moisture, Temperature and Air Quality, (d) Climate Change, Sustainability and Cities, (e) Smart Buildings and Digital Engineering, (f) Life Cycle Assessment and Circular Economy, (g) Energy Use, Retrofit and Net Zero Carbon, and (h) Systems Thinking and Transdisciplinarity.

We are part of The Bartlett Faculty of the Built Environment, #1 for Architecture and Built Environment studies in the world according to the QS World University Rankings (2024).

This book outlines our 60-year-long history at The Bartlett, a portfolio of our teaching programmes and innovative pedagogies, our current research projects and our plans moving forward. Each theme has defined the major research challenges in the next 10 years in collaboration with our industrial and academic partners globally.

Dejan Mumovic, Professor of Building Performance Analysis, IEDE director

Michael Davies, Professor of Building Physics and the Environment, IEDE Deputy Director for Academic Careers

Marcella Ucci, Professor of Healthy and Sustainable Buildings, IEDE Deputy Director for Academic Operations

WE ARE THE BARTLETT

IEDE in numbers

£3.7
million research grants (2023/2024)

130
staff and doctoral researchers

73
doctoral researchers

£15
million research portfolio

£10.8
million annual budget

£5.7
million tuition fees (2023/2024)

27
active research projects

40%
female professors

50%
female visiting professors

65%
international staff

37%
female academics

Facts we like

UCL is ranked 9th in the world (Qs, 2025)

UCL is No. 2 int the UK for research power (Research Excellence Framework 2021)

UCL ranks 1st in the UK and 5th globally in QS sustainability rankings

The Bartlett is ranked 1st in the world for Architecture and the Built Environment (QS, 2025)

The Bartlett is where the UK's most world leading and internationally excellent built environment research is undertaken (Research Excellence Framework 2021)

91% of our research has been deemed world leading or internationally excellent (Research Excellence Framework 2021)

The Bartlett is No 1 for research power in the Built Environment (Research Excellence Framework 2021)

1 out of 4 UCL Royal Academy of Engineering Centres of Excellence in Sustainable Building Design (2013, jointly with the Bartlett School of Architecture and UCL Civil Environmental and Geomatic Engineering)

3 consecutive EPSRC platform grants (2006 - 2022) awarded to "well established, world leading research groups"

IEDE plays significant role in 3 out of 7 national UKRI hubs on Health Co-benefits of Transition to Net Zero

What does an IEDE academic do (on average)?

Publish 5 peer-reviewed journal papers

Teach 5 MSc students

Teach 5 MEng students

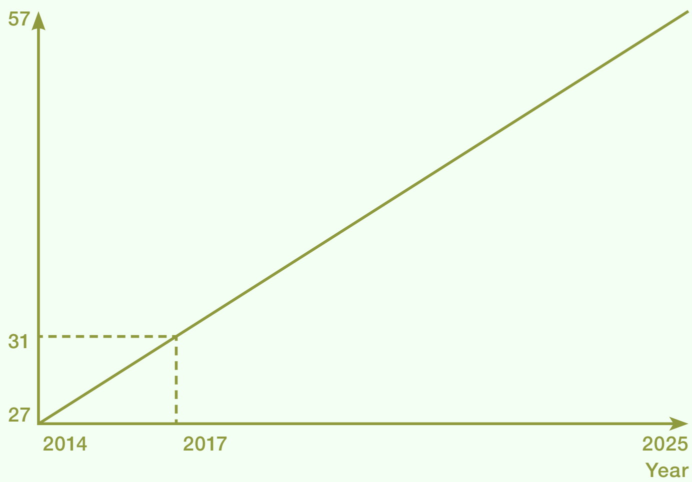
Supervise 2 doctoral researchers as the principal supervisor

Supervise 1 postdoctoral researcher

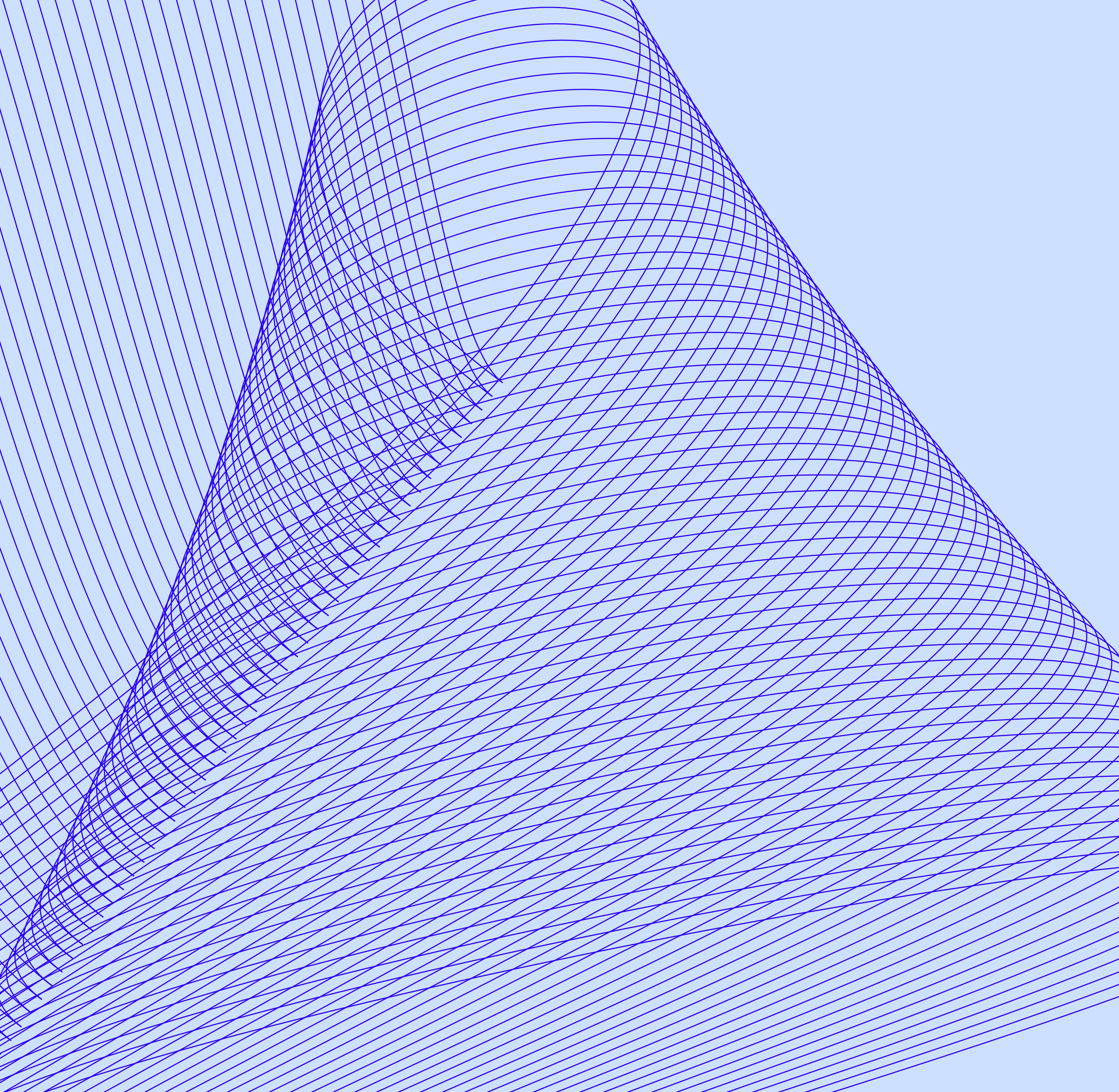
Lead one research project

Manage £0.5 million research portfolio as the principal investigator

Number of staff (academics and post-doctoral researchers)



HISTORY



INTRODUCTION

Central House is located just off Euston Road, a short distance from Euston Station (image credit: Edward Barrett)

In 2025, The Bartlett's Environmental Design and Engineering (EDE) discipline marks its 60th anniversary, a milestone that reflects a proud legacy of shaping the future of the built environment. Since its founding in 1965, EDE has played a leading role in bringing scientific inquiry to built environment design and policy, driven by the imperatives of the times, and in close alliance with industry and government.

At the heart of EDE's success have been its excellent teams, who have continued to evolve its principles and ways of working. A series of leaders have built upon the legacy of their predecessors, bringing their individual perspectives and priorities to the department. Over the decades, their research focus and close collaborations with industry and policy makers have been instrumental to the programme's direction.

EDE's foundations were laid in the 1960s by **Prof. Richard Llewellyn-Davies**, a pioneering architect with a keen interest in science and technology. His philosophy described architecture as a 'meeting ground' of numerous other disciplines: environmental design, structures, lighting, acoustics, planning, economics, psychology and history. He established EDE within The Bartlett School of Architecture by appointing **Ralph Hopkinson** as Professor of EDE in **1965**. This was a time when Modernism was gaining momentum, driven by new materials and construction techniques grounded in scientific and technological innovation. As a precursor to what we now call 'user experience' (UX) in design, Llewellyn-Davies' focus on the relationship between buildings and their occupants reflected the industrial design innovations of its time. While this concept has been characteristic of EDE's research and teaching throughout its 60-year history, the term **UX design**, coined by Apple in the 1990s, has only recently been gaining wider recognition in building design and engineering.

Over the years, EDE's scope has been expanded to tackle some of the most pressing challenges of the times, from energy crises to human health and climate change. Bringing together expertise from diverse fields, including physics, medicine, engineering, sociology, psychology, computation and architecture, has become EDE's signature approach. This diversity has been essential to addressing real-world problems, pushing the boundaries of research, and delivering impactful projects that have shaped both policy and industry standards.

As The Bartlett Faculty grew, EDE forged new alliances between emerging schools and disciplines, leading to significant growth in research and teaching. The story of EDE is also one of its formative relationship with The Bartlett School of Architecture. As the two departments have diverged and converged over the past six decades, the role of scientific research in shaping design has remained central to EDE's story.

Between 1965–1992, environmental design thinking was at the core of architectural education, fuelling an '**Experimental Revolution**' at The Bartlett. From 1992, EDE became a formative part of The Bartlett School of Graduate Studies, growing into a '**Research Powerhouse**' within the Faculty of the Built Environment. When EDE became the **Institute for Environmental Design Engineering** (IEDE) in 2014, it continued to drive a '**Revolutionary Evolution**' from within The Bartlett School of Environment, Energy and Resources, transforming built environment research, design and engineering. By renewing ties between The Bartlett School of Architecture and other UCL departments, the new Institute for EDE instigated the creation of new transdisciplinary undergraduate and postgraduate courses to qualify a new generation of designers with the knowledge to address complex emergent challenges.

Today, UCL IEDE's work intersects science, design and consultancy, with a research portfolio that spans from building physics to human behaviour. The programme's success is built on decades of collaboration across disciplines and industries, with its alumni continuing to lead in their fields. Its at-times turbulent evolution can be best described in three distinct phases:

— 1965–1991: Experimental Revolution
— 1992–2013: Growing a Research Powerhouse
— 2014–present: Revolutionary Evolution

TIMELINE

1960	Richard Llewelyn- Davies joins The Bartlett
1965	Ralph Hopkinson is appointed as first Chair in Environmental Design and Engineering (EDE)
1967	Richard Llewelyn- Davies' planning practise works on the design of Milton Keyne
1969	Ralph Hopkinson receives RIBA Honorary Fellowship for establishing lighting as a core architectural skill
1975	Wates House opens, housing state of the art EDE equipment
1978	MSc in Environmental Design and Engineering Launched
1987	MSc in Light and Lighting launched
1989	Pat O'Sullivan is appointed as Haden-Pilkington Professor of EDE and Head School and Dean of the Faculty of the Built Environment at The Bartlett School of Architecture, Building, Environmental Design and Planning
1992	The Bartlett School of Graduate Studies is founded; MSc in Facility and Environment Management is launched
2001	EDE Alumna May Cassar establishes the Centre for Sustainable Heritage
2006	EPSRC Platform Grant (2006-11) awarded for the Complex Built Environment Systems project

2009	Alumnus Tadj Oreszczyn establishes UCL Energy Institute
2011	EPSRC Platform Grant (2011-16) awarded for The Unintended Consequences of Decarbonising the Built Environment project
2013	EDE was named by the Royal Academy of Engineering as a Centre of Excellence in Sustainable Building Design
2014	The UCL Institute for Environmental Design and Engineering is established
2017	Historic third EPSRC Platform Grant for ‘Built Environment Systems Thinking MSc in Health, Wellbeing and Sustainable Buildings launched MEng Engineering and Architectural Design (EAD) launched
2018	IEDE expands to new research and teaching facilities in HereEast, Queen Elisabeth Olympic Park MSc in Smart Buildings and Digital Engineering established
2021	MEng EAD receives triple accreditation: architecture (RIBA/ARB), civil engineering (JBM) and building services engineering (CIBSE)
2022	MEng EAD is awarded Happold Brilliant award for best accredited course by CIBSE BSc/MEng Sustainable Built Environments, Energy and Resources launched
2025	60 Years of Environmental Design and Engineering at the Bartlett

EVIDENCE BASED DESIGN AND THE BARTLETT

The Bartlett Summer show 2024 (image credit: Richard Stonehouse)

Lord Richard Llewelyn-Davies 1960-1975

Richard Llewelyn-Davies joined The Bartlett in 1960 as Professor of Architecture and Head of School. His academic aim was 'trying to bring architecture into closer touch with developments in the natural and social sciences', and to provide a stronger link between the professions and academia. He based it upon his previous research into the planning and the architecture of hospitals which he conducted at the École des Beaux-Arts, Paris, then the Institute of Advanced Studies, Princeton (a first for an architect) and at the Nuffield Foundation, London. In bringing The Bartlett forward from a Beaux Arts tradition, that he was well versed in, it produced a dynamic that continues to this day with organisational changes along the way. On a professional level, he integrated practice with his academic work from the start. He founded a planning practice in 1960 that was responsible for planning the innovative new town of Milton Keynes, Buckinghamshire in 1967. His work was recognised in 1969 with his appointment at as Professor of Urban Planning of the newly named Bartlett Faculty, School for Environmental Studies. He presided over the transition of The Bartlett from the Pearson Building to the newly built Wates House.

The gestation of EDE was during the dynamic cauldron of post war Britain. From the beginning in 1960, the teaching of architects was revolutionised to include a wider range of environmental topics and a stronger academic base. The changes were quickly phased in over the following years and, as Llewelyn-Davies' first end of year letter to students shows, there were also plans for postgraduate courses. By 1965 there were distinctly different audiences for The Bartlett's work that helped draw academic undergraduates and professionals together. With a direct appeal to mature candidates, the MSc EDE also helped the social mobility of 1960's Britain. It provided a stronger academic foundation to practicing architects and especially building engineers to help deal with newer, more sophisticated building systems and architectural constraints. The offering of an MSc to part-time students was also innovative for the times, a continuing characteristic of the way that the EDE course has developed to this day, in its appeal to a worldwide audience and addressing emerging issues, informed by research.

Richard Llewelyn-Davies had a strong vision for ground-breaking Masters programmes which would bring science into architecture through evidence based design. This statement is taken from his inaugural speech: "....Finally, in every [department] except architecture, post graduate studies and research is vigorously pursued. It is through these studies that the subject is advanced, new knowledge is developed and future teachers are trained.....". The record of UCL EDE alumni speaks for itself.

Alan Penn, Dean of The Bartlett, UCL's Faculty of the Built Environment said that the establishment of UCL IEDE marked the coming of age of ideas about built environment research first pioneered by Richard Llewelyn-Davies at The Bartlett in the 1960's, but under the radically different context that we see today where globalisation, new technology and the challenges of climate change and sustainability create real urgency and a widespread perception of the centrality of the built environment to the future of the planet, economy and society at large.

HEADS OF ENVIRONMENTAL DESIGN & ENGINEERING

A side view of Central House including St Pancras Church located just off Euston Road (image credit: Edward Barrett).

Professor Ralph Galbraith Hopkinson 1965-1976

Ralph Galbraith Hopkinson was invited by Richard Llewelyn-Davies in 1965 to occupy the first chair of Environmental Design and Engineering, a post he held until 1976. The new professorial chair, funded by GN Haden and Pilkington Brothers had a long lasting influence over The Bartlett and EDE, enlarging the scope of architectural education to incorporate environmental and human factors.

Hopkinson drew on his research experience from the Building Research Station, Garston, into visual comfort in buildings, together with his previous work on lighting at the pioneering Hirst Research Laboratories, Wembley, of the General Electric Company to develop the design of lighting of schools, hospitals and roads in the UK. His work in establishing lighting as a core skill of architects was recognized by RIBA in 1969 via an appointment as an Honorary Fellow.

He was later Dean of the Faculty of Environmental Studies, 1972-74. His own engineering-architectural cross-over underpinned the development of EDE and its cross-disciplinary appeal.

Professor John Musgrove 1978-85

John Musgrove was Haden-Pilkington Professor of Environmental Design and Engineering 1978-85 and Head of The Bartlett School of Architecture and Planning 1980-85. There were a number of academic questions that he, in common with fellow colleague Bill Hillier at The Bartlett and with other peers in the Welsh School of Architecture and elsewhere were grappling with.

The principal question was how to address the disparity between the high quality, readily available research into the avoidance of building problems, and the poor performance of buildings being designed and erected at that time. Potential solutions lay in bridging the gap between an increasingly codified approach to design adopted by professionals and a potential approach being advocated based on a quasi-scientific, holistic process for design.

The resulting influential RIBA Research paper postulated a suitable design process. The cross-disciplinary MSc EDE aimed to help professionals to bridge that gap and ensure that all factors had been considered. Hence, over the years, the course has evolved from considering the integration of building specific architectural, engineering, technical, human and legislative issues to include wider scale sectoral and infrastructural effects.

Professor Newton Frank Watson 1986-88

Newton Frank Watson was Haden-Pilkington Professor of Environmental Design & Engineering and Head of The Bartlett School of Architecture & Planning (1985-88) and Dean of the Faculty of Environmental Studies, (1986-88). He had a long architectural academic career commencing in the late 1950's as Resident Fellow, Nuffield Foundation Division for Architectural Studies. After a spell as lecturer in Architecture, Polytechnic of North London he joined The Bartlett in 1957 as lecturer and was to have a long association with it. With occasional spells as a visiting professor in the USA, he was for many years its Professor of Architecture (1969-85). He lectured Bartlett undergraduates on lighting in the mid 70's and combined academic work with consultancy on innovative projects that led to his receipt of an award from the Illuminating Society of America for his lighting design of the London Stock Exchange (1974), and the Tate Gallery (1980).

Professor Pat O'Sullivan 1989-1999

Pat O'Sullivan was appointed in 1989 as the Haden-Pilkington Professor of Environmental Design and Engineering, Head of School and Dean of the Faculty of the Built Environment at The Bartlett School of Architecture, Building, Environmental Design and Planning. He had previously held the Chair of Architectural Science at the University of Wales from 1970.

By profession an engineer, he was also invited to advise significant public and private organisations, including the Houses of Parliament, the BBC and a range of Mechanical and Electrical specialist companies. The 90's were a challenging time both in the direction and funding of education in the UK that, in common with many other heads, occupied many an hour. He kept an arm's length, strategic overview of EDE and occasionally lectured, providing high level insights into client perspectives of building services and design issues. He encouraged the cross-over between academia and professional work and promoted the adoption of external visiting lecturers, peers in their fields. During his tenure, EDE staff including Tadj Oreszczyn, Chris Hancock, Alan Young, Casimir Iwaszkiewicz and others contributed to the success of an innovative government funded initiative, the Energy Design Advice Scheme. It provided independent energy design advice, drawing on best practice and research, to a wide range of significant building projects and clients. These included commissioning clients as well as internationally respected architects and engineers. Its pioneering work impacted on many building sectors including commercial, heritage, educational and industrial buildings, both on a project and strategic level. The experience of practice and research continue to feed into the EDE course to this day.

"Pat was a great political mover…
a mover and shaker."
Professor Emeritus Michael Corcoran

Professor Tadj Oreszczyn 2000-2009

Originally appointed by Pat O'Sullivan in the late 80's, Tadj lectured on energy and building environment including condensation risk and mites. With a background in physics and cold bridge analysis he had an ability to convert numbers and energy concepts into readily understandable issues.

His in-depth knowledge of energy interactions in buildings was well regarded by government departments and EDE students were occasionally willing guinea pigs for testing out new building regulations. In the mid 90's he was director of one of the government funded Energy Design Advice Scheme centres based at The Bartlett, providing energy advice to architects and engineers as well as to building clients.

This example of crossing over research and best practice into industry was in the long established tradition of The Bartlett. Tadj was for many years the head of the UCL Energy Institute and is now the head of the new The Bartlett School of Environment, Energy and Resources (BSEER), of which UCL IEDE is a part.

Professor Mike Davies (2010-2017)

Mike began his research work looking both at very specific areas of interest – multi-dimensional heat flows and shading devices - but also whole building performance. Via the monitoring and modelling of building performance Mike is now seeking to understand how buildings can optimally minimise their production of CO2 whilst maintaining healthy and comfortable conditions.

He is Professor of Building Physics and Environment at UCL, and acts as the Director of the Complex Built Environment Systems (CBES) Group. CBES is an EPSRC Platform Grant funded group with a major focus on the 'Unintended Consequences of Decarbonising the Built Environment'. The work of CBES has impacted on a range of relevant key national and international policy formulations.

Professor Dejan Mumovic (2017-present)

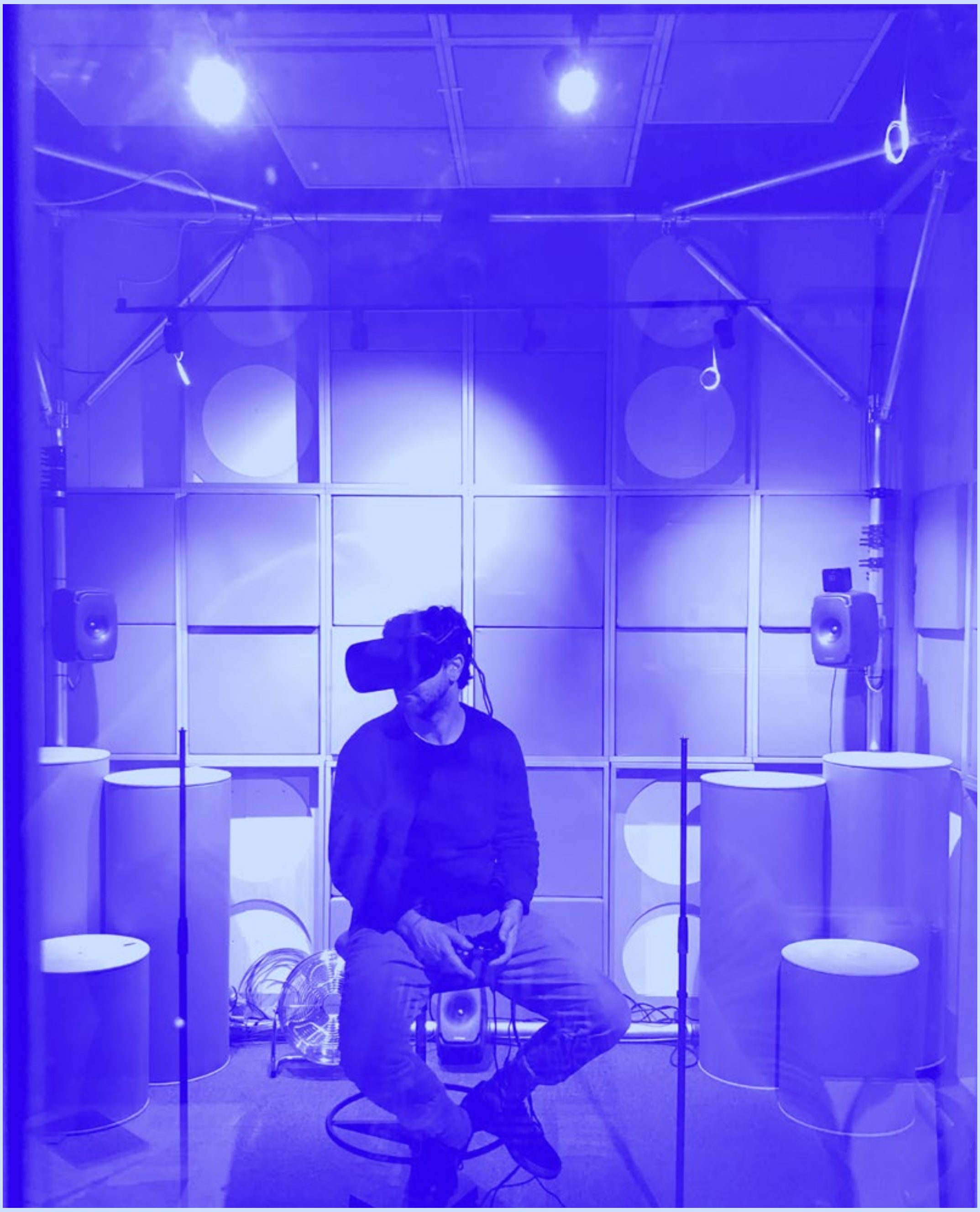
Professor of Building Performance Analysis, Fellow of CIBSE and IBPSA. Dejan is a building scientist with a background in heating, ventilation and air conditioning engineering and the extensive experience of monitoring and modelling work in the field of the built environment.

Dejan was a driving force of the MEng Engineering and Architectural Design, and the dual degree programme BSc | MEng Sustainable Built Environments, Energy and Resources. He is the editor of "A Handbook of Sustainable Building Design and Engineering: An Integrated Approach to Energy, Health and Operational Performance" (2010,2018 and 2026)

Dejan is the CIBSE Board member (2025-2028), Expert Adviser for Climate Change and Decarbonisation at Department for Education (2023-2025). Dejan was Co-founder and Inaugural Chair of CIBSE Education Guild (2024), Co-founder of CIBSE School Design Group (2007), and Co-founder of IBPSA-England (2006).

UCL Here East building located at the Queen Elizabeth Olympic Park (image credit: Edward Barrett).

1965–1991: EXPERIMENTAL REVOLUTION



A laboratory experiment in the Here East lab, using an IVR HMD and the 2nd order Ambisonics speaker array (image credit: Tin Oberman).

The story of Environmental Design and Engineering (EDE) at The Bartlett begins during the transformative 1960s, a period marked by student unrest across Europe, and calls for new ways of thinking across academia. **Prof. Richard Llewellyn-Davies**, who took leadership of The Bartlett in 1960, set out to revolutionise architectural education, moving away from the traditional Beaux-Arts model that prioritised form and artistic expression.

For Llewellyn-Davies, architecture was more than an art; it was a science, deeply connected to the environments in which buildings were located and the lives they influenced. Every detail of the architecture, he believed, could and should be measured, studied and improved, with evidence informing design and persuading clients to embrace it. This focus on data and evidence in design was a precursor to today's performance-based approaches. The interaction between buildings, environments and users became a constant thread throughout EDE's evolution. His approach introduced a new emphasis on science, technology and evidence-based design – a shift that would provide EDE's direction for decades.

This research-driven ethos was evident in Llewellyn-Davies' work on hospital design. With support from the Nuffield Foundation, he led research into hospitals and other building typologies. Llewellyn-Davies, along with John Musgrove, who would lead EDE in the early 1980s, studied how buildings affected occupants. Their research examined issues such as how patients navigated spaces, the impact of lighting and air quality, and how room orientation could optimise solar angles for comfort and efficiency. This pioneering work laid the groundwork for EDE's future focus on building performance, exploring human comfort through air quality, lighting and spatial orientation.

Llewellyn-Davies believed that The Bartlett's teaching methods should expand beyond drawing alone. He encouraged students to use writing and speaking as essential tools alongside drawing to better communicate their work to a broader audience. First-year students, equipped with cameras and typewriters instead of traditional drawing tools, were tasked with exploring urban areas to observe interactions between people, transport and architecture – emphasising the human experience in design.

Under his leadership, a research culture took root, fostered by new postgraduate courses and a team of specialists, and attracting visits by celebrated figures including **Buckminster Fuller**, **Max Fordham** and **Michael Humphreys**. Through his consultancy work in the 1960s, Llewellyn-Davies developed a close collaboration with **Ralph Hopkinson**, who, as head of the Building Research Station, the precursor of today's BRE, had made significant contributions to lighting design. Hopkinson was a natural choice to become the **first Haden-Pilkington Professor of Environmental Design and Engineering**, a role established in 1965, marking the creation of EDE. With support from GN Haden and the Pilkington Brothers, a leading glass manufacturer attracted by The Bartlett's expertise in thermal comfort and daylighting, this industry partnership marked EDE's first formal collaboration with industry, a hallmark of its approach for decades to come.

Hopkinson's research informed award-winning projects, such as the London Stock Exchange Market Hall and the 1978 Tate Gallery extension. His work exemplified how science could drive design, with EDE becoming established as a hub of interdisciplinary research and collaboration, influencing government policies and standards, as well as academia.

Llewellyn-Davies believed architecture should address the social and environmental challenges of the time by merging the physical sciences with the social sciences, such as psychology and sociology, to create healthy buildings and urban spaces. As his ideas gained momentum, he became Dean in 1970, renaming The Bartlett as **The Bartlett School of Environmental Studies** to reflect his vision for integrating architecture, planning and environmental design. While some at the time felt this gave science priority over creativity in design, it was a pioneering approach that brought global concerns about population growth, environmental issues and social upheaval into architectural education.

1965–1991: EXPERIMENTAL REVOLUTION

In 1967, Llewellyn-Davies' own architectural practice started work on the masterplan for the new town of Milton Keynes. As his attention turned to the urban scale, he appointed **Newton Frank Watson** as Professor of Architecture in 1969. Watson was a specialist in lighting design who shared Llewellyn-Davies' commitment to research-based teaching in the built environment. Watson lectured The Bartlett's undergraduates on lighting in the mid-1970s, while combining academic work with consultancy. He collaborated closely with Ralph Hopkinson on the lighting design of projects including the award-winning London Stock Exchange and the Tate Gallery, with contributions from **Dr Kevin Mansfield**, a Bartlett graduate, who joined EDE in 1977.

The move to **Wates House** in 1975 marked a turning point for EDE, enabling the creation of state-of-the-art facilities such as acoustic and lighting labs, a wind tunnel, a thermal chamber and an artificial sky. These labs were revolutionary. The lighting lab, for instance, was one of the first in the UK dedicated to exploring how natural light affects human perception and wellbeing. These facilities enabled researchers and students to test their hypotheses and designs with physical models in controlled, real-world conditions. Their work influenced not only design practice but also the evolution of building regulations across the UK. Following Hopkinson's retirement in 1978, **John Musgrove**, a longtime colleague of Llewellyn-Davies, assumed the role of **Haden-Pilkington Professor of Environmental Design and Engineering**. By 1980, he had also become Head of The Bartlett School of Architecture and Planning, further consolidating environmental design within architectural education. While this continued to raise contention about the balance between technical rigour and creative expression, the priority of Musgrove and his peers was to develop high-quality research to address the widespread issues of poor building performance evident in construction at the time.

Their efforts culminated in a seminal Royal Institute of British Architects research paper advocating an integrated design process, a concept that became the foundation for the **MSc in Environmental Design and Engineering** course launched in 1978 and accredited by the Chartered Institution of Building Services Engineers (CIBSE), and led to close collaboration with the Institution that continues to this day.

The MSc EDE programme aimed to equip professionals with tools to address architectural, technical, human, legislative and infrastructural factors in the design process. Under Musgrove's leadership, the programme evolved to emphasise sectoral and infrastructural impacts. Core Faculty members like **Ron Hawkes** (Acoustics), **Jimmy Longmore** (Thermal), **Ted Rowlands** (Lighting) and **David Loe** (Lighting) were joined by visiting experts, including **Michael Humphreys** (Human Comfort) and **Joe Lyons** and **Lou Bedocs** (Lighting).

Throughout the 1980s, EDE grew, attracting alumni who returned as lecturers and consultants. These instructors taught the impacts of lighting and daylight on psychology, physiology and architecture. The artificial sky allowed students to evaluate lighting solutions in 'real time' with physical models, supported by skilled craftsmen like **Chris Malet**, **Richard Grant** and **Francis Milson**, who built specialised equipment and models for the labs.

Lighting became a key theme, and by 1987 demand from The Bartlett and the lighting community led to the creation of the **MSc in Light and Lighting**, developed by David Loe and co-funded by Philips, based at Philips House on Torrington Place. Loe's curriculum integrated technical, aesthetic and architectural aspects of lighting. The programme, later led by **Kevin Mansfield** and **Peter Raynham**, became instrumental in shaping the UK's lighting industry, training around one-third of the UK's lighting design community.

Llewellyn-Davies' interdisciplinary research culture incubated other pioneering strands. In the early 1970s, **Bill Hillier**, **Alan Beattie** and **Adrian Leaman** explored how spatial configurations affect social behaviour, leading to the founding of the Space Syntax Lab in 1972. Dr Julienne Hanson, a key colleague of Bill Hillier, played a critical role in advancing the theoretical and analytical framework for Space Syntax, emphasising the relationship between spatial configuration and human behaviour in built environments. Her research explored how spatial design affects human interactions, including social inclusion, accessibility and community life.

In parallel, another area of expertise emerged at The Bartlett, fuelled by the shared interest of **Llewellyn-Davies** and his longtime colleague **Bev Nutt** in enhancing the flexibility and manageability of buildings over their lifespans. Nutt believed strongly in aligning property investment and design decisions with lifecycle considerations, including building use, maintenance cycles and the accommodation of evolving business needs. In 1992, Nutt brought in **David Kincaid**, a pioneer in facilities management (FM) education, to co-develop the **MSc in Environment and Facility Management** at EDE. This programme positioned The Bartlett at the forefront of FM – an emerging field in the early 1990s that combined operational efficiency with environmental priorities. Kincaid championed a curriculum addressing the full lifecycle of buildings, equipping graduates to manage buildings sustainably and adapt them to meet changing user requirements.

By the late 1980s, architecture and architectural education were undergoing a profound ideological shift. Moving beyond the minimalist, functionalist principles of Modernism, architects increasingly embraced complexity and contradiction, reflecting a turbulent, rapidly changing global landscape. With post-war resource shortages and the 1970s fuel crises fading, innovations in structural engineering began to free designers from material constraints, enabling a shift away from Modernism's purist architectural language. This new era favoured designs embracing fragmentation and pluralism, evident in the emergence of visually expressive forms.

It was also a period of accelerating globalisation, with large corporations turning to architecture to project their expanding international influence. The collapse of the Soviet Bloc in 1989 further opened new markets for Western architects, who began engaging with building typologies that reflected Eastern Europe's capitalist transformation through high-profile architectural competitions. British architects and urbanists responded with more fragmented, organic design approaches, influenced by the deconstruction of large-scale, Communist-era projects.

As EDE's research expanded, staff and students increasingly called for an architectural curriculum that addressed the sweeping changes reshaping the design world. Around this time, the 1988 Education Reform Act, introduced under Prime Minister Thatcher, centralised control over university budgets and performance standards, introducing more market-driven structures. Faced with student strikes and significant changes in higher education, The Bartlett needed a radical change in leadership.

In response, the university appointed **Prof. Pat O'Sullivan** in 1989 as both Head of The Bartlett and Dean. Known for his transformative work at Cardiff University's School of Architecture, where he established a world-class, interdisciplinary research capability grounded in design, O'Sullivan set out to reshape The Bartlett. Within three years he had made key appointments that would define the Faculty's direction for decades.

Early on, he secured a 'new blood' lectureship to balance research and teaching responsibilities, awarding it to **Tadj Oreszczyn**. O'Sullivan, then part of the Legionnaires' Disease Inquiry team, needed someone who could step in for him who would be driven enough by empirical research principles to climb cooling towers to collect samples for evidence. Tadj would go on to transform EDE into a powerhouse of research in environmental design and energy.

Though seen as a disruptor, O'Sullivan was widely regarded for his engaging personality and care for people. **Alan Penn**, a longtime Bartlett student and self-employed research assistant when O'Sullivan arrived, recalled how O'Sullivan stopped him in the corridor, learned about his precarious contract, and encouraged him to pursue an academic career. Both Penn and Oreszczyn went on to lead key institutes and schools at The Bartlett, playing central roles in the Faculty's consistent ranking among the top in the world.

Amid demands for change in the School of Architecture, O'Sullivan supported The Bartlett's search committee in appointing **Peter Cook** in 1990 and **Christine Hawley** in 1993, bringing avant-garde energy to the architecture programme. By 1992, as Cook steered the programme towards creative and cultural expression, the more research-intensive groups, including **EDE**, **Lighting**, **Facilities** and **Space Syntax**, formed **The Bartlett School of Graduate Studies**, appointing **Dr Julienne Hanson** as its first Director. This new school relocated from Wates House to Torrington Place, establishing a dynamic interdisciplinary hub for advanced research and consultancy in the built environment. The new headquarters for the School of Graduate Studies, Philips House, became a centre for studies in environmental design, energy efficiency and building performance.

During this first phase, EDE fostered an interdisciplinary culture, drawing expertise from fields including physics, chemistry, engineering and social sciences to address real-world challenges of the built environment through scientific models. This research-led approach introduced scientific rigour to architecture through influencing policies, challenging norms and building industry alliances. Graduates took on leadership roles in industry, championing EDE's evidence-based approach which considered both design and performance, while others continued advancing research at the School of Graduate Studies. From its early focus on visual, thermal and human comfort to its pioneering postgraduate programmes, this period laid the foundation for EDE's future as a leader in sustainable building design and environmental engineering.

Toby Cambray demonstrates a modular heat pump system at UCL Here East (image credit: Edward Barrett)

UCL Here East building, viewed from Parkes Street
(image credit: Edward Barrett).

1992–2013: GROWING A RESEARCH POWERHOUSE

The UCL East Marshgate building at Stratford Waterfront Campus is the largest single building at UCL, and part of the largest expansion of the university since it was founded almost two hundred years ago (image credit: Edward Barrett)

With **Pat O'Sullivan** as Dean from 1990, EDE consolidated its strengths in applied building science while expanding into new areas of environmental design research. Recognising the need for a focused postgraduate research environment, O'Sullivan devised the establishment of The Bartlett School of Graduate Studies in 1992, positioning it independently of undergraduate programmes in architecture and planning. The School provided EDE with a dedicated platform for research and teaching, free from traditional departmental constraints, and laid the groundwork for The Bartlett's emergence as a leader in sustainable environmental design. As Chair of the UK's Building Regulations Advisory Committee (BRAC) and a member of the Government Committee inquiry into Legionnaires' Disease, O'Sullivan also shaped national policy, influencing building standards that continue to impact the built environment.

The appointment of physicist **Tadj Oreszczyn** as a 'new blood' lecturer in 1992, shortly after EDE's move to **Philips House** (now 1–19 Torrington Place), marked a pivotal moment for EDE. Initially hired to support O'Sullivan with his work at BRAC, the inquiry into Legionnaires' Disease and his research into sick building syndrome, Oreszczyn was also tasked with developing an expansion plan for the Environmental Design and Engineering **MSc**. At the time, the course was structured around four distinct modules: lighting, acoustics, ventilation and thermal performance. Oreszczyn integrated these themes and introduced energy as a central focus, aligning the programme with emerging questions about indoor comfort and energy efficiency. The restructured course earned accreditation from the Chartered Institution of Building Services Engineers (**CIBSE**) in 1993, establishing the MSc as a leading pathway for careers in sustainable building design and services engineering. **Alan Young**, the course director until 2007, played a key role in the programme's development and carefully selected a diverse cohort of students from varying professional backgrounds. The mix of full- and part-time students enriched the learning experience, fostering a dynamic exchange of ideas and practical insights.

In 2007, **Ben Croxford** became course director of the **MSc in EDE**. A computer systems and electronic engineer by training, Croxford brought expertise in air pollution and intelligent monitoring systems to EDE's research projects. As Director of Teaching and Learning at The Bartlett School of Graduate Studies (2010–2014), he expanded the MSc curriculum, introducing solar and thermal analysis software and inviting thought leaders from the growing sustainable design community to provide their input. Croxford's leadership of the MSc reinforced EDE's commitment to data-driven, collaborative learning and equipped students with cutting-edge tools to model buildings' environmental interactions. EDE alumni have shaped practices worldwide. Notable EDE MSc graduates from these years include **Ricardo Moreira**, founder of XCO2 Energy, **Anis Abou Zaki** at Foster + Partners and **Saud Muhsinovic** at Mott MacDonald.

In the early 1990s, as a lecturer in EDE, Tadj Oreszczyn noted the broader implications of an MSc student's research on energy consumption in conservatories. Building regulations at the time promoted conservatories as buffer spaces, but a study of 10 homes revealed that 9 conservatories were heated during winter, as occupants used the additional space year-round. When scaled to the UK housing stock, the extra energy consumption would negate the predicted savings from upcoming improvements to Part L of the building regulations.

Despite limited funding for energy-related research at the time, Oreszczyn secured a grant to study 5,000 conservatories. The findings were striking: homes with conservatories consumed more energy for heating than those without, and double-glazed conservatories used twice as much energy as single-glazed ones due to year-round usage. These conclusions exposed the unintended inefficiencies of building regulations and helped secure funding for further **empirical and forensic building performance studies**. This research was significant – at the time, little data existed on how buildings performed thermally, what their actual energy use was and what the impact of occupant behaviour was on performance.

As research funding expanded, Oreszczyn also explored the relationship between moisture, indoor environmental quality (IEQ) and mould growth, developing predictive models to identify conditions that fostered these issues. A notable example of his applied research was the investigation of leaks in the House of Lords debating chamber. Led by **Bill Bordass**, a leading expert in building performance diagnostics, the building sleuths traced the source of dripping water to roof leaks. In the process, they uncovered fundamental flaws in the air-conditioning system, highlighting the value of rigorous, **real-world building investigations**.

Forensic investigations to gather empirical data on building performance became a defining feature of Tadj Oreszczyn's leadership at EDE. Since the 1960s, theoretical models and lab testing had been used to predict how buildings should operate, leading to widespread reliance on simulations by the early 1990s. Modelling performance was seen as cost-effective and precise enough to guide building services design and compliance with regulations, allowing the industry to bypass empirical verification of performance in use.

However, as the gap between designers and building users widened, little attention was paid to how construction quality, user behaviour and modelling assumptions affected real-world outcomes. Over the next two decades, EDE research followed the practice of measuring actual building performance under operational conditions and comparing it with design simulations. This work uncovered many unintended consequences and led to new methods for scaling findings to stock level, revealing the systemic impacts of the performance gap. The collaborative environment at the School of Graduate Studies supported a growing body of research rooted in empirical data collection and analysis.

By the 1990s, buildings were widely recognised as accounting for over 50% of UK energy consumption and nearly 50% of CO^2 emissions, prompting increased governmental focus on energy efficiency. To support energy-conscious design, the government of the time introduced the **Energy Design Advice Scheme (EDAS)**, offering free energy consultancy for properties over 5,000m². Thanks to the credentials of Nutt, O'Sullivan and Oreszczyn, UCL was appointed to run EDAS's south east regional centre. Under Prof. Oreszczyn's direction, EDAS procured and peer-reviewed consultant energy reports for non-domestic refurbishments, providing invaluable insights into simulation practices of the time. Between 1992 and 1998, Oreszczyn managed consultancy funding for EDE, growing its research base while forging vital industry connections.

EDE's role in EDAS underscored a significant gap in building services expertise geared towards energy efficiency and sustainability. While UK building services engineers were typically trained as mechanical engineers, EDE's MSc programme was able to fill this gap by offering a distinctive approach rooted in architectural education. It emphasised occupant experience, balancing indoor air quality, thermal comfort, lighting and acoustics with environmental considerations. As energy efficiency and environmental consciousness gained traction, the programme's integration of sensory experience and environmental design positioned EDE as a leader in the field.

One of the EDE MSc students, **May Cassar**, joined the course in 1990 under Pat O'Sullivan's guidance. Her Master's research on the **Courtauld Institute Galleries** investigated environmental conditions in 'sealed' spaces and their impact on artwork preservation, foreshadowing the principles of post-occupancy evaluation (POE) or building performance evaluation (BPE). After a successful career in historic building conservation, Cassar returned to The Bartlett School of Graduate Studies in 2001 to establish the **Centre for Sustainable Heritage**, now the Institute of Sustainable Heritage, which she continued to lead until 2023. Her expertise in air, light and thermal environments in heritage contexts has shaped cross-disciplinary strategies for museums and historic buildings, addressing energy and climate challenges while honouring the specific needs of cultural spaces.

UCL's MSc in Light and Lighting was launched in 1987, adopting a cross-disciplinary approach that quickly earned it a global reputation. In the 1990s, the programme expanded its curriculum and produced pioneering research on visual comfort and safety, shaping UK lighting standards. Under **Kevin Mansfield** and **David Loe**, collaborations with manufacturers provided students with access to cutting-edge technology and career opportunities. When funding from Philips ended in 1995, support continued through the **Lighting Education Trust (LET)**, established with **CIBSE** to coordinate industry contributions and reinforce the programme's value. **Stephen Cannon-Brookes**, an experienced lighting consultant, was appointed part-time to support this programme. Notable Light and Lighting MSc graduates include **Florence Lam** at Arup, and **Ruth Kelly Waskett** at Hoare Lea.

In 1996, **Peter Raynham** joined as LET lecturer, leading impactful research in street lighting, school lighting and daylight modelling. His **EPSRC-funded research on glare** (2009–2013), focused on 'human-centric' lighting that balanced visibility, comfort and energy efficiency, informed the energy-efficient transformation of UK street lighting, **reducing energy use by a third** while improving public safety and comfort. The **MERLIN research projects**, starting in 2011, further advanced intelligent lighting technologies, enhancing energy savings and occupant wellbeing. These findings influenced manufacturers and policy makers, cementing the MSc programme's role in advancing energy-efficient, adaptive lighting solutions.

In 1992, **Bev Nutt**, **Pat O'Sullivan** and **David Kincaid** identified the need for formal training in managing sustainability-driven building portfolios, leading to the creation of a postgraduate programme in **Facility and Environment Management (FEM)**. This programme integrated skills in areas such as occupancy surveys and **BPEs** to enhance occupant wellbeing and productivity. BPEs enabled facilities managers to gather user feedback on comfort, health and satisfaction, fine-tuning systems such as lighting, ventilation and thermal controls. This proactive, data-driven approach aligned adjustments with sustainability and cost-saving goals, supporting lifecycle-focused building management.

McLennan strengthened interdisciplinary collaboration and secured accreditation from the **British Institute of Facilities Management (BIFM)** and the **Royal Institution of Chartered Surveyors (RICS)**. He also embedded the culture of applied industry-driven research via the UKRI Knowledge Transfer Partnerships (KTPs) scheme. Thanks to his work, IEDE is still one of the most active participants in this scheme among the higher education institutions. Under McLennan, with the support of **Alexi Marmot**, Professor of Facility and Environment Management, and Course Director **Dr Ljiljana Marjanovic-Halburd** (now Head of the Engineering School at the University of Leicester), the MSc FEM programme that had flourished in London was also run in Singapore from 2010 in collaboration with the Building and Construction Authority there. The aim was to educate the top tier of the 'green collar' workforce needed to manage a sustainable Singapore. In 2010, Prof. Michael Pitt, the Editor of the Journal of Facilities Management, was appointed to strengthen the FEM research portfolio. He later transferred to The Bartlett School of Sustainable Construction to establish the pioneering Digital Innovation Built Asset Management MSc.

By the late 1990s, as available research funding surged, Tadj Oreszczyn sought to extend building-level findings to understand the UK's entire building stock. In 1999, **Philip Steadman** and **Harry Bruhns** joined UCL from the Open University, bringing their expertise in mapping building typologies and energy use. Their earlier work on the National Non-Domestic Building Stock project (NDBS) became a precursor to the 2004 **CaRB** project, which evaluated energy-efficiency interventions from a sociotechnical perspective. Collaborating with UCL's **CASA** (Centre for Advanced Spatial Analysis), they integrated building data with GIS and visual analytics, advancing understanding of non-domestic energy use and supporting the shift to low-carbon building stock.

Building Performance Evaluations during the late 1990s raised awareness of the 'performance gap': the difference between expected and achieved energy efficiency of buildings.

During this time, the pioneering **PROBE** project assessed the '**performance gap**' in around 20 buildings, by comparing design expectations with operational outcomes. Led by a team that included **Adrian Leaman** (BUS), **Bill Bordass** (Usable Buildings Trust), Robert Cohen (Verco) and John Field (Native-Hue), the project provided insights into occupant comfort and energy use, shaping practical recommendations that were later captured in **CIBSE's Technical Memorandum (TM) 22**. Widely published in the CIBSE Journal, these findings influenced UK building standards by emphasising evidence-based improvements to energy efficiency and occupant wellbeing.

While EDE did not directly contribute to PROBE, its significance reflected the broader shift in industry and policy towards addressing mismatches between design expectations and actual building performance. This momentum also gave impetus to academic and industry collaborations involving larger datasets, further advancing research into building performance and operational outcomes.

1992–2013: GROWING A RESEARCH POWERHOUSE

In 2005, EDE partnered in the **CarbonBuzz** initiative to highlight the performance gap using crowdsourced energy data. Inspired by Alan Penn, **Dr Judit Kimpian**, Director of Sustainable Architecture and Research at **AHR**, secured funding through **UrbanBuzz** to create an online platform comparing energy use and carbon emissions from design to operation. Supported by Innovate UK, **CIBSE**, **Royal Institute of British Architects (RIBA)** and **BRE**, with input from **Harry Bruhns** and advice from PROBE team members, CarbonBuzz became the first UK online tool to benchmark buildings' energy performance, enhancing transparency in the sector.

The introduction of **Display Energy Certificates** (DECs) by the UK Government in 2006 further emphasised operational energy reporting in public buildings, positioning the UK as a leader in this area. DECs were underpinned by benchmarks from **CIBSE's TM46**, developed with contributions from Bruhns and PROBE collaborators. Together, this work laid the foundation for subsequent Innovate UK projects, including the **BPE** studies of 50 non-domestic and 100 domestic buildings starting in 2010, developing a generation of UK experts in building performance research.

Building on relationships established during his EDAS leadership in the 1990s, **Tadj Oreszczyn** secured a series of research and consultancy projects with the **Office of the Deputy Prime Minister** (ODPM) in 2003. These four-year projects informed the evolution of UK building regulations during the transposition of the EU Energy Performance of Buildings Directive (EPBD). The ODPM sought to address potential unintended consequences of new energy performance standards, such as the impact of airtightness on indoor air quality.

The research enabled EDE to expand its team, welcoming **Dejan Mumovic**, a mechanical engineer with a PhD in applied computational fluid dynamics, in 2003, and **Mike Davies**, a building physicist, in 2004. While Davies, working with **Ian Ridley**, primarily focused on domestic projects and Mumovic on non-domestic buildings, together they addressed a broad range of building types and challenges. Their research examined the interplay between building fabric, systems and occupant behaviour, conducting BPEs and POEs. These studies conducted during ODPM-related research provided concrete evidence of the 'performance gap', revealing discrepancies in energy consumption, occupant comfort and HVAC performance. These findings exposed the limitations of existing design models and simulation tools, driving a shift towards realistic, data-driven approaches to building performance.

Around this time, physicist **Bob Lowe** joined the team, bringing further expertise in housing decarbonisation and strengthening EDE's interdisciplinary approach. EDE's projects with the ODPM also included studies on humidity, mould growth and house dust-mite prevalence, alongside research into condensation risks and ventilation system standards. With colleagues from AECOM, the EDE team combined generalised measurements with computational fluid dynamics to refine ventilation design guidance for schools, influencing the **Building Schools for the Future** programme (2004–2010) and the retrofitting of around 700 schools. Mumovic and Palmer (AECOM) co-founded the **CIBSE School Design Group** (2007), updated the **Department for Education's guidance Building Bulletin 93** and shaped CIBSE design guides including **CIBSE TM57 Integrated School Design** (2015). By embedding BPEs in their research, EDE reinforced the importance of continuous performance monitoring and occupant feedback. These practices continued to influence academic and industry approaches to sustainable building design well beyond the ODPM projects.

During **Tadj Oreszczyn**'s leadership, EDE secured The Bartlett's first **EPSRC Platform Grant** in 2006, establishing the **Complex Built Environment Systems Group (CBES)**. CBES focused on reducing greenhouse gas (GHG) emissions, adapting buildings to climate change, and improving health, comfort and productivity in and around buildings. This interdisciplinary group brought together academics from environmental design, light and lighting, cultural heritage and environmental facility management to explore the physical performance of the built environment and its implications for energy use, health, conservation and climate change.

The grant provided bridge funding to further enhance CBES's interdisciplinary capacity, enabling investments in equipment and personnel while supporting bridging funding for key researchers. It catalysed solutions to practical challenges in designing, constructing and managing sustainable environments, and fostered research into the complexity and unintended consequences of building performance.

Several postgraduate students who contributed to ODPM and parallel research projects joined EDE through the grant, later became distinguished professors. **Hector Altamirano-Medina**'s research on moisture in buildings led to his co-founding of the **UK Centre for Moisture in Buildings (UKCMB)** in 2016, where, at the time of writing, he serves as academic director. **Marcella Ucci**, now **Professor in Healthy and Sustainable Buildings**, began her career studying environmental control of dust mites and later launched the Health, Wellbeing and Sustainable Buildings MSc. **Rokia Raslan**'s PhD revealed disparities in accredited UK energy compliance software, bolstering the case for standardised methods. Now **Professor of Built Environment Decarbonisation**, her work focuses on 'hard-to-decarbonise' homes. **Anna Mavrogianni**, who completed her PhD on modelling overheating risks in housing, later became Professor of Sustainable, Healthy and Equitable Built Environment. **Gemma Moore**, an applied social scientist, collaborated with **Alan Penn** and **Ben Croxford** on perceived versus measured IEQ, gaining expertise in co-design and participatory processes for sustainable, healthy urban environments. Now **Associate Professor and the Programme Director for the Health, Wellbeing and Sustainable Buildings MSc**, she leads in research explaining successful processes of transformational change towards healthy built environments. The Platform Grant not only advanced research at EDE but also cultivated home-grown expertise, supporting career-defining contributions to research, teaching and the development of industry standards.

RSPB Environment & Education Centre in the east of London (image credit: Photo by MagicBones / Shutterstock)

In 2009, amid a surge in energy and climate research funding, **Tadj Oreszczyn** established the **Energy Institute** to expand energy-related research across sectors. With EPSRC and Research Council UK support, the **Centre for Energy Epidemiology** was created, focusing on large-scale data analysis of energy demand and benchmarking. Oreszczyn was joined by **Bob Lowe**, **Mark Barrett**, **Harry Bruhns** and **Phil Steadman**. As Oreszczyn shifted his focus to the Energy Institute, **Prof. Alexi Marmot**, a leading authority in facility and environment management, became Head of The Bartlett School of Graduate Studies from 2009 until its dissolution in 2014. During her tenure, Marmot advanced workplace and facilities management (FM) research, aligning it with The Bartlett's broader sustainability goals. It was under her leadership that **EDE**, alongside The Bartlett School of Planning, relocated from Torrington Place to the newly refurbished **Central House**, strategically positioned near **Wates House** and **Euston Station**. The move provided EDE with upgraded facilities and closer proximity to colleagues at The Bartlett, fostering collaboration and reinforcing its role within the Faculty of the Built Environment.

At the same time, **Prof. Mike Davies** succeeded Oreszczyn as **Head of EDE**, ushering in a **diversification of EDE's research**, the start of a long-term expansion into health and climate change-related built environment research. Building on its strong foundation in IEQ, occupant behaviour and BPEs, EDE leveraged the interdisciplinary expertise in heritage, lighting and FM that was needed to engage with these emerging areas. Research and consultancy initiated by the Office of the Deputy Prime Minister further bolstered EDE's readiness to tackle new research themes and projects.

Momentum around health and climate research grew with EPSRC-funded projects such as the Local Urban Climate Model and its Application to the Intelligent Design of Cities (**LUCID**) (2007–2011), led by Mike Davies. This project addressed overheating risks in urban heat islands by developing methods for mapping local temperatures and air quality. Its outcomes influenced London's urban greening strategies and informing the Greater London Authority's Climate Change Adaptation Strategy (2011) and DEFRA's 2012 Climate Change Risk Assessment. Collaborative projects such as **PUrE** explored strategies to balance airtightness, ventilation and thermal resistance with indoor air quality, energy efficiency and occupant wellbeing. Meanwhile, the **SWERVE** project produced software to provide climate hazard information at actionable scales, such as extreme heat and cold, high winds, flooding and drought. Another EPSRC-funded research project developed computer-based models to simulate the hygrothermal performance of structures, creating innovative deployable measurement systems to diagnose and mitigate moisture problems in buildings. These projects increasingly deployed digital modelling methods to better understand building physics and climate adaptation.

EDE's expertise was showcased in the NERC-funded **Air Pollution and Weather-Related Health Impacts project** (2011–2014) that developed one of the earliest stock models for energy use and pollutant dispersion. The study uncovered links between socioeconomic deprivation and pollutant exposure, revealing that the years of life lost by most deprived communities was 4% higher than those in the least deprived groups, due to PM2.5 exposure. It also highlighted that populations in homes prone to overheating faced elevated heat-related mortality risks, emphasising the need for ventilation strategies that balance protection from outdoor air pollution with indoor air quality.

EDE's rapid expansion into health-related research was greatly supported by its close collaboration with **Prof. Paul Wilkinson**, a distinguished epidemiologist from the **London School of Hygiene and Tropical Medicine** (LSHTM). Prof. Wilkinson worked closely with **Mike Davies** on assessing health outcomes associated with energy-efficiency measures in buildings, providing invaluable epidemiological insights that enriched EDE's research. In collaboration with international teams, CBES researchers demonstrated that health outcomes are closely tied to the implementation and maintenance of energy efficiency measures. Their findings contributed to influential publications, including the landmark 2009 Lancet series on the public health benefits of climate change mitigation. This work also informed key discussions at the 2009 UN Climate Change Conference, highlighting the critical role of health considerations in strategies for GHG reduction. During this period, **Ian Hamilton** (now Vice Dean of Research at The Bartlett) and **Jonathon Taylor** (now Associate Professor at Tampere University of Applied

Sciences in Finland) emerged as internationally recognised academics working at the intersection of climate, energy and health in the built environment. The series' findings showed that climate policies could deliver immediate public health benefits alongside long-term environmental gains. This research influenced UK building regulations and supported Department of Energy and Climate Change discussions on policies like the '**Warm Front**' programme. By integrating health into climate action plans, it promoted policies linking health and sustainability. Highlighting the co-benefits of health-focused climate change mitigation, the series shaped future health, climate and housing policies nationally and internationally.

EDE also advanced indoor air quality research, particularly in schools. The **SINPHONIE** project (2010–2014), led by **Dejan Mumovic**, involved 38 institutions across 25 countries, and assessed how primary school environments impact children's health. Research in six London schools studied CO^2 levels and health indicators, providing insights into air quality and ventilation strategies. It revealed a stark connection between poor indoor air quality in schools and a range of health issues in children, including respiratory, eye and systemic disorders. Pollutants like PM2.5, benzene and ozone were linked to higher odds of these symptoms, while increased ventilation rates and balanced indoor temperatures were found to alleviate some conditions. The findings challenged the reliance on CO2 levels alone as a measure of healthy air, emphasising the need for a broader set of indoor air quality standards in building design. The study also highlighted the economic and health benefits of reducing pollutants such as nitrogen dioxide near primary schools, offering actionable insights for creating healthier learning environments. Outcomes led to the Indoor Air Quality in London's Schools report (2018), commissioned by Mayor of London Sadiq Khan to review existing evidence and investigate the level of indoor air pollution in London's schools. **Lia Chatzidiakou** (now Senior Research Associate at the University of Cambridge) was co-author of the report and became an internationally recognised academic on indoor air quality monitoring and data analytics.

These projects revealed the often conflicting drivers between energy efficiency and IEQ, particularly when resilience to occupant behaviour was overlooked. Under Mike Davies' leadership, EDE's research increasingly focused on health-oriented building performance, drawing on medical insights and attracting diverse funding to understand and address challenges such as overheating, urban climate resilience, systems thinking and acoustics. This work was supported by an **extension to the Platform Grant** awarded in 2012 which focused on the **unintended consequences of decarbonising the built environment**.

Building on earlier work on complex built environment systems, it introduced expertise in **systems dynamics**, and a methodology to analyse and influence the interconnections within the built environment. To address the complex interplay of factors affecting building performance, occupant health and environmental impacts at both building and city scales, Prof. Davies invited **Alex Macmillan** (then at the University of Auckland) to formalise a systems-thinking approach within EDE's research methodology. Macillan's expertise brought invaluable insights into urban environmental impacts, enhancing EDE's ability to address multifaceted sustainability challenges.

In the early 2010s, EDE strengthened industry collaborations through several **KTPs** with leading practitioners such as **Max Fordham**, **Buro Happold** and **Philips**. These partnerships helped refine research outcomes and created new services tailored to industry needs.

EDE also participated in the **LoLo Centre for Doctoral Training in Energy Demand**, a collaboration with the Energy Institute and Loughborough University that fostered a network of PhD students addressing interdisciplinary environmental design challenges.

Under Alan Penn's leadership as Dean of The Bartlett from 2009, EDE was able to expand its **doctoral research** opportunities. The EPSRC-funded **Virtual Environments, Imaging and Visualisation** (VEIV) programme, led by **Anthony Steed** from the UCL Department of Computer Science, incorporated digital engineering into built environment research, and supported 20 industry-co-funded doctoral studies at EDE. Penn appointed **Dejan Mumovic** to lead doctoral collaborations, further strengthening EDE's industry partnerships.

EDE's partnerships extended to leading UK architectural practices, including **Hawkins\Brown**, **Feilden Clegg Bradley Studios**, **AHMM** and **Foster + Partners**, as well as construction sector leaders such as **Buro Happold**, **Arup**, **Skanska** and **Amey**. These collaborations embedded research insights into practice, further cementing EDE's influence on the built environment. Doctoral graduates **Greig Paterson** (Director at Drees & Sommer), **Craig Robertson** (Head of Sustainability at AHMM) and **Joe Williams** (former Partner at Feilden Clegg Bradley Studios, now Head of Sustainability at Bywater) and **Carrie Behar** (Head of Sustainability at the Useful Simple Trust) emerged as industry leaders.

Around this time, **Innovate UK's Low Impact Buildings** programme catalysed interest in healthy buildings and decarbonisation. EDE played a key role in these government-funded projects, helping to train a generation of experts in building performance. Highlights included the **UKCMB**'s contribution to the **Retrofit for the Future** programme and the continued development of **CarbonBuzz**, the online benchmarking platform co-developed with UCL to highlight the performance gap. **Sung-Min Hong** began his PhD in 2009, mentored by the much-admired **Harry Bruhns**. When Harry tragically lost his battle with cancer in 2011, Hong gradually took over UCL's energy benchmarking research, revealing the scale of the 'performance gap' across building sectors. His work supported professional bodies in advocating for performance in use and underpinned **CIBSE's** next-generation **benchmarking platform**. Hong was appointed a lecturer in 2018. Meanwhile, **Yair Schwartz** tackled embodied and operational carbon challenges in housing, thereby broadening EDE's research impact. Upon completing his postdoctoral fellowship, Schwartz was appointed lecturer in 2020.

The **Innovate UK Building Performance Evaluation Programme** provided live case studies for **Esfandiar Burman**'s doctoral research that included long-term energy performance analysis, IEQ monitoring, operational versus designed performance reviews and Building Use Studies (BUS). His work covered five educational buildings plus innovative office and residential projects, and was co-funded by AHR and Innovate UK. The findings supported AHR's advocacy for performance validation, improving the quality and delivery of energy-efficient designs. These outcomes were further reflected in guidance issued by **RIBA** and **CIBSE**, reinforcing their impact on industry standards. Burman was appointed lecturer in 2017.

The doctoral research programme created a dynamic community of young professionals, equipped with the expertise to confront the climate challenge and design for a rapidly changing world. It also significantly contributed to EDE's research outputs. The Bartlett's 2014 Research Excellence Framework exercise revealed the largest quantity of world-leading outputs in its field. EDE's Impact Case Studies were led by Raynham and Davies.

Research by **Raynham** led to the adoption of white light in residential roads and city centres throughout the UK, enabling an energy saving of 30–40% while providing a better quality of street lighting. As a result, by 2014 there were c.1,200,000 conventional streetlights with white light sources and a further c.220,000 LED lanterns that emit white light. Conservative estimates suggest that this changeover to white light saved 113GWh of electricity in 2012, thus reducing the UK emissions of CO2 by 45.5Mt.

Research led by **Davies** has contributed to a fundamental shift in global understanding of the possible health impacts of carbon mitigation measures and has thereby informed relevant policy formulation. At regional and national levels, research has informed London's Climate Change Adaptation Strategy, led to changes in the building regulations for England and Wales, and produced a tool used by the UK Department of Energy and Climate Change to inform aspects of its Energy Efficiency Strategy. International impacts of CBES arose both from its broad influence on policy makers' awareness and understanding of the implications of energy-efficiency policies, and from more specific contributions to the development of World Health Organization guidance.

The years spanning from 1992 to 2013 generated a critical momentum behind EDE's research approach that led to further transformation of The Bartlett Faculty.

UCL East Marshgate building at Stratford Waterfront Campus is the largest single building at UCL, and part of the largest expansion of the university since it was founded almost two hundred years ago (image credit: Edward Barrett).

2006-2022: EPSRC PLATFORM GRANTS

View from Central House 4th floor, looking along Upper Woburn Street towards Euston railway station (image credit: Edward Barrett).

Over the last decade UCL IEDE has received three Engineering and Physical Sciences Research Council (EPSRC) Platform Grants.

These prestigious awards of funding are given to what the EPSRC calls 'well-established, world-leading research groups' and have given the Institute a flexible foundation, allowing the creation of a long-term research strategy.

EPSRC Platform Grant (2006–11): Complex Built Environment Systems

The Institute's first Platform Grant enabled the establishment of a multidisciplinary research group that was able to grow, evolve and innovate while carrying out pioneering research, publishing influential papers and books and winning international prizes.

EPSRC Platform Grant Renewal (2011–16): The Unintended Consequences of Decarbonising the Built Environment

The Institute's second Platform Grant enabled the establishment of a strategic programme of research to transform the understanding of the system-level effects of climate change policies. Conventional scientific approaches designed to analyse systems into simple components are limited in their ability to predict potential system outcomes. This grant is allowing new models to be developed to minimise the unintended consequences of future climate change policies.

EPSRC Platform Grant Renewal (2017–22): Built Environment Systems Thinking

The Institute's third Platform Grant developed a new strategic programme of research aimed at informing the scientific understanding of the systemic nature of a sustainable built environment. The grant supported retention and career development of key staff members through bridging between projects and by funding concept development project work. The grant also allowed BSEER to build knowledge exchange through industry fellowships, collaborative projects and internships for platform staff.

2014–PRESENT: REVOLUTIONARY EVOLUTION

The Marshgate Café (image credit: Edward Barrett).

By 2014, Environmental Design and Engineering (EDE) at The Bartlett had entered a new phase of its evolution, marked by structural and teaching innovations. To support the growing momentum of research across The Bartlett Faculty, Dean Alan Penn initiated a major restructuring of departments, leading to the creation of The Bartlett School of Environment, Energy and Resources (BSEER). The formation of BSEER brought together two existing institutes – the Energy Institute (EI), led by Prof. Bob Lowe following Prof. Tadj Oreszczyn's tenure, and the Institute for Sustainable Resources (ISR), established in 2011 under Prof. Paul Ekins – with two newly created institutes: the Institute for Environmental Design and Engineering (IEDE), led by Prof. Mike Davies, and the Institute for Sustainable Heritage (ISH), directed by Prof. May Cassar.

Prof. Tadj Oreszczyn, BSEER's inaugural director, introduced a federated model that balanced shared resources with the autonomy of each Institute. This structure enabled collaboration across disciplines while allowing each Institute to manage its research, teaching and budgets independently. Shared professional services streamlined operational processes and provided essential support for funding applications, freeing academic staff to focus on their fields of expertise.

This restructuring coincided with a period of ambitious but inconsistent national policies. While the UK's Net Zero 2050 target was enshrined in law, the absence of robust regulatory initiatives since 2010 left gaps in driving meaningful progress, particularly as applied to retrofitting and holding the sector accountable for building performance. Rising university tuition fees also increased the reliance on international students within UK academic institutions, shifting priorities and intensifying competition for global talent.

Despite these headwinds, climate change awareness in the sector grew, creating a need for evidence-based approaches to sustainable design and environmental resilience. Businesses, particularly in the architectural and engineering sectors, sought clear guidance and skilled professionals to navigate the complexities of decarbonisation, energy efficiency and climate adaptation.

In response to these challenges, teaching became a focus of IEDE's then Deputy Director, Prof. Dejan Mumovic, who recognised that The Bartlett was well positioned to create transdisciplinary undergraduate training programmes, which would equip a new generation of built environment professionals to address the uncertainties and demands of a rapidly evolving sector. With the support of Dean Alan Penn, the then Director of the Bartlett School of Architecture, Prof. Bob Shiel, and the Department of Civil, Environmental and Geomatic Engineering, The Bartlett launched the collaborative Engineering and Architectural Design MEng course (MEng EAD), coinciding with Mumovic's appointment as Director of IEDE in 2017.

The MEng is the first integrated design course of its kind in the UK to be fully accredited by the Chartered Institute of Building Services Engineers (CIBSE), the Royal Institute of British Architects (RIBA) and the Joint Board of Moderators (JBM). It also offers Architects Registration Board Part 1 exemption, enabling graduates to pursue leadership roles across architecture and engineering. CIBSE Gold Medal winner and distinguished engineer, communicator and Honorary Prof. Tim Dwyer's advice on accreditation criteria supported the design of both undergraduate programmes.

Co-designed by IEDE (Dejan Mumovic, Tim Dwyer), the Department of Civil, Environmental and Geomatic Engineering (Dina D'Ayala, Liora Malki-Epshtein) and The Bartlett School of Architecture (Oliver Wilton, Luke Olsen and Bob Sheil), the course at the time of writing is led by Dr Luke Olsen (BSA) in collaboration with Dr Sam Stamp (IEDE) and Prof. Jose Torero (CEGE). This flagship studio-based programme marked a renewed convergence between architecture and engineering, just as scientific research took centre stage in built environment education. Design tutorials are led by tutors from all three disciplines, recognised as thought leaders and highly skilled in digital design, analysis and fabrication tools. The MEng EAD trains students in advanced design methodologies and expertise in their implementation and resolution. Drawing inspiration from IEDE's scientific and sociocultural approach, it encourages students to investigate the complex interactions between people, buildings and their environments through design projects. Informed by occupant-focused research and user experience (UX) design principles, the course has fostered innovative approaches to spatial and material design. Student projects have received widespread acclaim for their architectural creativity and for demonstrating technical rigour and evidence-based methodologies that are fundamental to engineering. Together, these teaching methods present a new paradigm for architectural education in the age of the climate crisis. The course received the prestigious CIBSE Happold Brilliant Award in 2022.

Collaboration with industry leaders has meant that the programme has remained firmly grounded in professional practice, embedding insights from consultancy into its teaching. The vision and expertise of two Honorary Profs – Ian Taylor, partner at architectural practice FCBStudios, and Ian Durbin, partner at Hoare Lea engineers – have been pivotal in shaping the course's cross-disciplinary curriculum.

Building on the success of the MEng EAD, The Bartlett launched the BSc/MEng in Sustainable Built Environments, Energy and Resources (SBEER) in 2022. While the MEng EAD focused on reconnecting architectural design with engineering, the SBEER programme is a response to the growing interdependence of engineering, economics and social sciences in achieving sustainability goals. Conceived by Profs Mumovic and Raimund Bleischwitz (Director of SBEER 2018–2021), all four departments at SBEER contributed to the development of this programme, born from the recognition that the engineering and economics of healthy, zero carbon built environments are deeply interdependent. Led by Dr Nahid Mohajeri (IEDE) and Dr Ricci Yue (ISR), the SBEER programme prepares students for roles as sustainability consultants and engineers capable of navigating the complexities of sustainable resource management and decarbonisation with advanced decision-making tools. Its curriculum emphasises systems thinking, developing students' expertise in data analysis, modelling and resource optimisation. The dual degree's structure offers pathways to BSc and MEng qualifications, attracting a diverse cohort of students passionate about tackling the multifaceted challenges of climate change, energy and urban resilience.

Both the MEng EAD and BSc/MEng SBEER programmes are taught at UCL's Here East campus and partially at Marshgate in the Queen Elizabeth Olympic Park, which opened in 2016 and 2023 respectively. This expansion has enabled IEDE to accommodate a rapidly growing student cohort with cutting-edge facilities that rank among the best of their kind globally. Redesigned by Hawkins\Brown architects after its use as the London Olympic Media Centre for the 2012 Games, Here East features open-plan studios, digital fabrication labs and modern lecture theatres, alongside advanced thermal chambers, lighting laboratories, an acoustic lab and urban data analysis spaces.

These world-class facilities have made the campus a hub of experimentation and creativity. Students construct experimental structures and installations inspired by environmental factors, utilising the digital manufacturing-enabled workshops as part of their studies, and test their designs in IEDE's specialised labs. The creative energy of Here East reinforces UCL's robust presence within the vibrant technology, media and education quarter surrounding the Olympic Park.

In addition to the MEng and BSc courses, two new MSc courses were launched by IEDE. The MSc in Smart Buildings and Digital Engineering, created in 2018 by Prof. Dimitrios Rovas and Dr Ivan Korolija, emerged during a period of rapid technological advancement in building services. By the mid-2010s, intelligent, self-learning smart systems and dynamic thermal modelling techniques were enabling designers to optimise energy use and indoor environmental quality. This evolution was reflected in the 2018 revision of the EPBD (EU Energy Performance of Buildings Directive), introducing the concept of 'smart readiness' that facilitates reporting on a building's systems capacity to learn and adapt to changing indoor and outdoor conditions while managing energy demand more effectively. IEDE has been at the forefront of this emerging discipline, leveraging Rovas's expertise in data information modelling and optimisation and Korolija's expertise in building systems modelling. This MSc represents a transformation in building services engineering education, aligning with the development of intelligent, integrated systems that prioritise both energy efficiency and occupant wellbeing. Students gain a solid foundation in the scientific principles of building systems design, combined with practical, data-driven approaches to optimise performance in terms of energy efficiency, indoor environmental quality and occupant health. Industry-standard tools such as EnergyPlus and DesignBuilder, alongside programming languages like Python, prepare students to tackle complex challenges in smart building design and operation. Led by Dr Valentina Marincioni and Dr Rui Tang, with contributions from Dr Yi Zhang, a pioneer of parametric design, the MSc equips graduates to lead in a new era of building services engineering, where technology, artificial intelligence and unprecedented access to operational data can lead to healthier, more sustainable environments.

The Health, Wellbeing and Sustainable Buildings MSc, launched in 2017, addresses the growing need for experts to lead the integration of health and wellbeing into the built environment. Developed by Dr Marcella Ucci, the course builds on decades of IEDE's pioneering research into the impact of the built environment on human health and performance. It equips students with the skills to design and operate buildings that promote health, comfort and productivity. Tackling challenges such as air quality, thermal comfort and urban resilience, students balance health and sustainability goals in both retrofit and new-build projects at many scales, while incorporating advanced modelling and monitoring techniques. The course is currently led by Dr Gemma Moore, Associate Professor in Health, Wellbeing and Communities, who brings expertise in co-production and participatory processes for stakeholder engagement in complex initiatives. Dr Helen Pineo and Dr Elizabeth Cooper, both now based in the USA, had previously led this course.

Over the past decade, IEDE has transformed the educational landscape of building services engineering by aligning teaching with cutting-edge research and fostering close links with industry. This ensures that students engage directly with contemporary challenges, graduating with the technical and theoretical expertise to design healthy, resilient and low-carbon buildings and cities. Through this work, IEDE has evolved building services engineering from a narrowly technical discipline to the creative and impactful design engineering of the built environment.

The transformative teaching initiatives of The Bartlett's IEDE have been driven by an equally revolutionary evolution in research. Research has not only created the content and direction of IEDE's teaching but has also been fuelled by the expansion of teaching programmes, in turn enabling more opportunities for research funding and collaboration. The same researchers who lead IEDE's innovative teaching programmes are also embedded in its research projects, ensuring a seamless integration of inquiry and instruction.

A defining characteristic of IEDE's research over the past decade has been its adoption of systems thinking – an approach that views the built environment as a complex network of interconnected systems. This perspective has provided a structured framework for tackling the multifaceted challenges of sustainability, health and resilience, offering new insights into the ways in which different components of buildings and cities interact. By using participatory methods and dynamic modelling tools, IEDE researchers have pioneered ways to design and test transformative interventions, thereby amplifying the real-world impact of their work.

The extraordinary growth in research has been propelled in part by the leadership of Prof. Mike Davies, who has led IEDE's expansion into the realm of human health through impactful collaborations with the London School of Hygiene and Tropical Medicine (LSHTM). UCL IEDE's success in securing substantial research funding, including three consecutive Platform Grants from the EPSRC, represents a significant achievement that has supported the diversification of research into areas critically affecting the sustainability of the built environment and the health and wellbeing of its occupants.

Only two built environment research groups in the UK, IEDE's Complex Built Environment Systems (CBES) and the Space Syntax Group, have secured three consecutive Platform Grants. This recognition has reinforced The Bartlett Faculty of the Built Environment's position as a national and global leader in research excellence. These grants enabled IEDE to adopt a systems approach, modelling the built environment as a dynamic, interconnected whole and fostering research that bridges disciplines and scales.

Alongside this, Prof. Dejan Mumovic aligned research priorities with government policies and industry needs, particularly in areas such as schools and indoor environmental quality. His ability to secure targeted research funding has ensured that IEDE's research remains directly relevant to pressing societal challenges.

Equally important has been IEDE's shared commitment to nurturing staff and fostering autonomy, inviting researchers to develop their own Themes of investigation. This inclusive approach has cultivated a vibrant and collaborative research environment, with staff empowered to explore diverse areas of inquiry. The establishment of cutting-edge facilities at Here East has further enabled IEDE researchers to combine experimental studies with empirical data, tuning digital models to real-world performance. These advancements have cemented IEDE's reputation for delivering high-impact research that addresses some of the most pressing challenges in the built environment.

Building on the systems approach supported by the Platform Grants, IEDE's research agenda has evolved into a set of dynamic and interrelated Themes. These Themes reflect the department's commitment to addressing critical challenges in the built environment while fostering interdisciplinary collaboration. Each Theme is chaired by a leading researcher, with contributions from a wide network of academics, doctoral researchers and industry partners, ensuring both depth and real-world relevance. The Themes demonstrate how systems thinking has been applied across scales, from individual buildings to entire cities, to generate actionable insights and drive transformative change.

EDE's research agenda addresses some of the most pressing challenges facing the built environment, with three interconnected Themes forming the foundation: Moisture, Temperature and Air Quality, Climate Change, Sustainability and Cities, and Energy Use, Retrofit and Net Zero Carbon. These Themes collectively explore how the design, operation and adaptation of buildings can balance health, sustainability and resilience goals while advancing national and global decarbonisation efforts.

The common thread across these activities is the focus on using empirical data to inform digital models, predicting and analysing dynamic interactions that shape environmental performance at both building and stock levels. Overheating has become a growing concern, prompting researchers to study heatwaves and passive adaptation strategies to protect vulnerable groups, including children, the elderly and those with health conditions. Indoor air quality (IAQ) is another focus. Innovative monitoring and modelling techniques are deployed to assess risks from pollutants and to map the interplay between occupant behaviour, ventilation and outdoor conditions.

Projects such as ARID (PI Mumovic) and ASPIRE (PI Mavrogianni) have examined how UK schools can adapt to climate change and decarbonisation targets while maintaining safe and productive learning environments. ARID's digital twin stock model of schools has provided new benchmarks for sustainable retrofitting, ensuring resilience to moisture risks and overheating. Meanwhile, ASPIRE has investigated the impact of ventilation and IAQ on student performance, producing actionable guidelines for school energy-efficiency retrofits that improve cognitive outcomes and reduce asthma incidence. Outcomes of this project informed the high-profile 2022 report on 'Adapting School Design for Learning, Health and Wellbeing during and Post-Pandemic'.

Collaborations with other universities continued to yield impactful results, with a strong focus on protecting vulnerable and elderly populations. The APEx projects (2019–2024), led by King's College London, quantified the effects of the London Ultra Low Emission Zone (ULEZ) on personal air pollution exposure, including for vulnerable groups. These findings informed the UK Clean Air Programme's strategies to safeguard at-risk populations.

In parallel, the ClimaCare project, a collaboration led by Davies with LSHTM, Oxford Brookes University, CIBSE, the Greater London Authority (GLA) and PRP Architects, analysed the impacts of heat on care home residents. Researchers developed novel monitoring techniques and modelling tools to assess overheating risks and evaluate passive mitigation strategies. The work revealed that, for example, heavyweight buildings generally maintained lower summer temperatures, while modern buildings benefited more from passive interventions. Night ventilation emerged as the most effective passive technique across all building types. The findings informed the UK Government's third Climate Change Risk Assessment (CCRA3), GLA strategies and CIBSE guidance on overheating risks in care homes, shaping policies to protect vulnerable residents.

Moisture in buildings remains a critical research focus due to its links to property damage and significant health risks. To address these challenges, IEDE established the

UK Centre for Moisture in Buildings (UKCMB), led by Prof. Hector Altamirano-Medina and Dr Valentina Marincioni. The Centre fosters a pioneering research community, develops tools and guidance, and played a key role in shaping standards such as PAS 2035, which the UK Government mandates for all publicly funded retrofit projects.

In addition to advancing policy and practice, the UKCMB hosts the prestigious biannual International Conference on Moisture in Buildings, a platform that accelerates knowledge sharing and innovation in this critical field. The UKCMB founding Director was Neil May (1962–2018), who is very sadly missed. In 2017 Neil was awarded an MBE 'for services to sustainability and energy efficiency in buildings and communities'.

Closely linked to Moisture, Temperature and Air Quality is the Climate Change, Sustainability and Cities Theme that addresses the challenges of urbanisation and climate change while exploring pathways to create resilient and sustainable cities. Researchers quantify urban environmental risks, such as extreme weather events and urban heat islands, and test solutions to mitigate these hazards. Their work also examines the health implications of climate change mitigation and adaptation measures, aligned with the UN Sustainable Development Goals (SDGs). The Theme is led by Associate Prof. Clare Heaviside, who joined the department in 2020 with a NERC Independent Research Fellowship to investigate the health impacts of urban heat islands through atmospheric modelling and health impact assessments.

Dr Heaviside also leads the HEROIC project (Health and Economic impacts of Reducing Overheating in Cities), funded by the Wellcome Trust, which explores how green infrastructure – such as parks, green roofs and walls – can reduce urban overheating and deliver health and economic benefits globally.

Precursors to these studies were the NERC-funded AWESOME project (Air Pollution and WEather-related Health Impacts) and the Wellcome Trust-funded SHUE project (Sustainable Healthy Urban Environments), completed in 2015 and 2017, respectively. These projects exemplified IEDE's interdisciplinary and systemic approach to tackling climate-related challenges. Early collaborations between Prof. Mike Davies and Prof. Paul Wilkinson from LSHTM revealed the increasing frequency of extreme heatwaves and the urgent need for coordinated measures across public health, social housing, planning and building regulations. Key findings demonstrated that occupant behaviour significantly affects overheating risks, that certain social housing flats overheated even in mild weather and that energy efficiency upgrades like internal insulation could exacerbate overheating without mitigation strategies such as night ventilation.

AWESOME and SHUE laid the foundation for a decade-long series of Wellcome Trust-funded collaborations between IEDE and LSHTM. These studies formalised IEDE's expansion into health impact research, scaling up its capacity to explore the built environment's broader effects.

Bloomberg European Headquarters in the City of London (image credit: Samuel Hagger / UnSplash)

Since 2018, the CUSSH (Complex Urban Systems for Sustainability and Health) project, funded by the Wellcome Trust, has worked with 13 partner organisations across four continents to help cities pioneer effective measures to achieve population-level changes in areas, including energy provision, transport infrastructure, green infrastructure, water and sanitation, and housing. Led by Prof. Mike Davies, this five-year initiative focused on six cities – London (UK), Rennes (France), Kisumu and Nairobi (Kenya), and Beijing and Ningbo (China) – identifying approaches to 'healthy urbanism' within the overlapping areas of net zero and public health. CUSSH has generated nearly 100 academic publications and 17 policy briefings on pre- and post-COVID-19 net zero public health interventions at dwelling, neighbourhood and city scales, contributing significantly to the evolution of urban sustainability.

Close collaboration with LSHTM continued following the sudden and deeply felt loss of Paul Wilkinson, a brilliant researcher and mentor devoted to fostering the next generation of experts. James Milner, a longtime IEDE collaborator, has carried forward Wilkinson's legacy at LSHTM, while Zaid Chalabi, a close colleague, joined IEDE as an Honorary Associate Professor, helping to ensure that Wilkinson's visionary research ideas endure.

The Energy Use, Retrofit and Net Zero Carbon Theme investigates the energy consumption and carbon intensity of buildings, developing methods to accelerate the decarbonisation of the UK's building stock in alignment with 2050 net zero targets. Researchers explore a range of retrofitting approaches, from light to deep interventions, combining technology-led and fabric-focused solutions. Social and economic barriers to retrofitting are also a key focus, alongside system upgrades such as heat pumps and adaptation measures to mitigate indoor overheating in a warming climate. The Theme is led by Prof. Rokia Raslan, who also serves as the UK representative on the Executive Committee of the International Energy Agency Energy in Buildings and Communities (IEA-EBC) Programme. Her expertise includes defining solutions for hard-to-decarbonise homes, improving domestic energy efficiency for the Sixth Carbon Budget, and assessing schemes such as Energiesprong and solid-wall insulation practices in UK homes.

A key contributor to this Theme, Dr Esfandiar Burman, conducted much of the precursor building performance evaluation work that laid the foundation for subsequent projects. His evaluations established methodologies to quantify the 'performance gap' between design expectations and real-world outcomes, influencing the broader field of building energy performance.

Building on this foundational work, the TOP (Total Operational Performance of Low Carbon Buildings in the UK and China) project, led by Prof. Mike Davies and funded by the EPSRC (2015–2019) in collaboration with Tsinghua University, used field measurements with novel instrumentation to explore how design and operation could deliver low-energy, low-carbon buildings with improved IAQ across schools, offices, hospitals and residential buildings. With contributions from Dr Burman, and many others, TOP developed recommendations to close the performance gap in energy use, carbon emissions and occupant satisfaction. These outcomes shaped industry standards, forming the basis for the CIBSE Technical Memoranda (TM) 61–64 (2020) and the updated TM54 (2022), which provided guidance on building performance modelling, monitoring and verification practices. This research informed the RIBA Publication Energy People Buildings – Making Sustainable Architecture Work, authored by Dr Judit Kimpian, Hattie Hartman (Sustainability Editor at the Architects' Journal) and Prof. Sofie Pelsmakers (UCL Energy Institute LoLo alumna), raising public awareness of how building performance evaluation feedback loops can enhance sustainable design.

Dr Samuel Stamp, now the IEDE's programme leader for the MEng EAD course, contributed to TOP with his expertise in building testing, monitoring and performance evaluation. Jointly with Prof. Mumovic, Dr Stamp also co-led the QUASIMODO (Improving Indoor Air Quality and Occupant Health through Smart Control of Windows and Air Purifiers) project, co-funded by Philips and the European Institute of Technology. Alongside IEDE researchers Dr Yan Wang and Dr Elizabeth Cooper (both now in the US), he developed IAQ monitoring strategies for projects in London, Helsinki and Antwerp. As UCL IEDE's Building Physics Monitoring Lead, Dr Stamp oversaw measurement and monitoring equipment, ensuring cutting-edge collaborations and teaching practices.

Collectively, this body of research has advanced energy-efficient technologies, innovative retrofitting practices and actionable solutions to close the performance gap, influencing both UK and global policy. By bridging building performance data with practical applications, the Theme continues to drive progress towards net zero goals while improving environmental quality and occupant satisfaction.

The Smart Buildings and Digital Engineering Theme at UCL IEDE investigates how digitalisation is revolutionising the design, construction and operation of the built environment. Researchers integrate emerging technologies such as the Internet of Things (IoT), artificial intelligence (AI) and data analytics to develop data-driven smart buildings capable of dynamically optimising energy use, indoor environmental quality and occupant experiences. By creating digital twins and advanced simulation models, the team contributes to the prediction and enhancement of building performance in real time.

Led by Prof. Dimitrios Rovas, the team includes Dr Ivan Korolija, Dr Farhang Tahmasebi and Dr Rui Tang, who collectively drive innovation through research and teaching. This Theme explores the application of collaborative design and project delivery platforms for multi-stakeholder interaction to achieve improved design and outcomes.

A significant contribution to the field is Dr Farhang Tahmasebi's co-edited book, Occupant-Centric Simulation-Aided Building Design, which explores how simulation tools can integrate occupant behaviour into building design processes to achieve more sustainable and effective outcomes. This publication has become a key resource for researchers and practitioners alike, reinforcing the importance of user-centred approaches in smart building design.

These advanced simulation techniques are also taught across UCL IEDE's MEng and MSc programmes, ensuring that students gain hands-on experience in programming cyber-physical systems and tools.

Recent projects include the development of smart control strategies that use occupant behaviour and environmental data to optimise building operations, and the application of machine learning algorithms to improve predictive accuracy in energy modelling. The team also works on integrating IoT-enabled sensors and real-time monitoring systems into design processes, enhancing the adaptability and resilience of buildings to changing conditions. For example, the Horizon-funded BuildON project (Affordable and digital solutions to Build the next generatiON of smart EU buildings) brings together 20 project partners from the region to develop a replicable 'Smart Transformer Toolbox' to enhance energy performance and smart capabilities in buildings through adaptive, affordable and smart readiness-aligned MAPO (Monitor, Assess, Predict, Optimise) services, utilising a universal building API and digital twins for real-time control, simulation and user-friendly decision-making, supporting the EU's energy transition and the REPowerEU Plan.

Through collaborations with industry partners and international research networks, the Smart Buildings and Digital Engineering Theme continues to shape the future of intelligent building systems, ensuring that digital solutions contribute to a more sustainable and occupant-centred built environment.

The Light and Lighting Theme at UCL IEDE builds on a rich legacy of prestigious research and teaching in this field, which has positioned the Institute as a leader in urban lighting. Following the partial retirement of influential figures, including Prof. Peter Raynham and Dr Kevin Mansfield, the Theme has benefited from the addition of Dr Mandana Khanie, a specialist in indoor environment quality and the use of lighting and daylighting. Arup Fellow and IEDE Honorary Prof. Florence Lam has been instrumental in the restructuring of the course. Dr Jemima Unwin, a leading researcher in urban lighting design leads the Theme. With support from Emeritus Prof. Peter Raynham, as well as the contributions from MSc in Light and Lighting lecturers and doctoral research students, the team is advancing investigations into the role of lighting in shaping human experience, health and safety.

One of the flagship projects in this Theme, MERLIN-2 (Further Empirical Evidence of Lighting for Pedestrians), funded by the EPSRC in 2015, explores how lighting can improve pedestrian safety and comfort in urban environments. By combining empirical evidence with advanced simulation tools, this follow-on project from MERLIN-1 has continued to inform the design of energy-efficient, human-centred urban lighting

The Fenchurch Building (The Walkie-Talkie) in the City of London, a skyscraper in London known for its distinctive shape that resembles a walkie-talkie (image credit: Seb Doe / UnSplash)

systems. UCL IEDE's research extends beyond urban contexts, leveraging facilities such as the dark room for experimental lighting studies to explore health impacts and vision-related issues. These facilities enable researchers to assess how lighting affects occupant behaviour and wellbeing, including studies using eye-tracking technology to understand how individuals navigate and respond to illuminated environments. The Light and Lighting academic team consult on various topics relating to lighting design. The Theme also prioritises integrating research into teaching, with findings from projects like MERLIN-2 enriching the curricula of IEDE's undergraduate and postgraduate programmes. Students engage with the practical and theoretical dimensions of lighting design, gaining insights into how evidence-based approaches can enhance safety, energy efficiency and human health. Through its interdisciplinary approach and state-of-the-art facilities, the Light and Lighting Theme continues to advance knowledge and inform policies for healthier and more sustainable lighting systems in urban and indoor spaces.

The Acoustics and Soundscapes Theme at IEDE was revitalised as one of Mumovic's first actions as Director, with the appointment of Prof. Jian Kang, a globally recognised authority and Fellow of the Royal Academy of Engineering, to lead this critical area of research. This appointment completed IEDE's representation across the scientific disciplines that shape human experience in the built environment. Under Kang's leadership, the acoustics team has grown significantly, incorporating both industry-leading research and practical applications. The team includes outstanding contributors such as Dr Francesco Aletta, who currently leads this theme, and, until recently, Dr Andrew Mitchell, a pioneer in applying machine learning techniques to acoustics. Additionally, Dr Tin Oberman, manager of the acoustics facilities at Here East, ensures that the state-of-the-art labs are well utilised for studies and collaborations. One of the flagship projects in this Theme is the SSID ('Soundscape Indices') project, funded by the European Research Council, which develops metrics to assess and design soundscapes in urban environments. Led by Prof. Kang, SSID is transforming the way sound is integrated into urban planning, emphasising its role in health, wellbeing and the quality of life in cities. The team's research extends beyond urban soundscapes to pressing global issues. For instance, Dr Aletta co-authored a CIBSE white paper on COVID-19, focusing on acoustic considerations in building design during the pandemic. This work reflects the department's interdisciplinary approach and its commitment to addressing real-world challenges. Through strong industry links, IEDE's acoustics research has influenced guidelines and standards, including the development of the ISO 12913 standards series on soundscape as well as contributions to CIBSE's guidance documents. The team's systems-thinking approach ensures that sound is studied not in isolation but as an integral part of the built environment, connecting to health, comfort and sustainability. With world-class researchers and cutting-edge facilities, IEDE continues to lead in acoustics research, combining traditional expertise with innovations in technology and data analysis.

The Life Cycle Assessment and Circular Economy Theme at IEDE explores the environmental impacts of the built environment across its entire lifecycle, from material extraction and manufacturing to construction, operation and end-of-life stages. This Theme addresses critical issues such as embodied carbon and operational carbon, and broader environmental impacts, including global warming potential (GWP), acidification, water use and ecosystem effects, aligning with the principles of the circular economy.

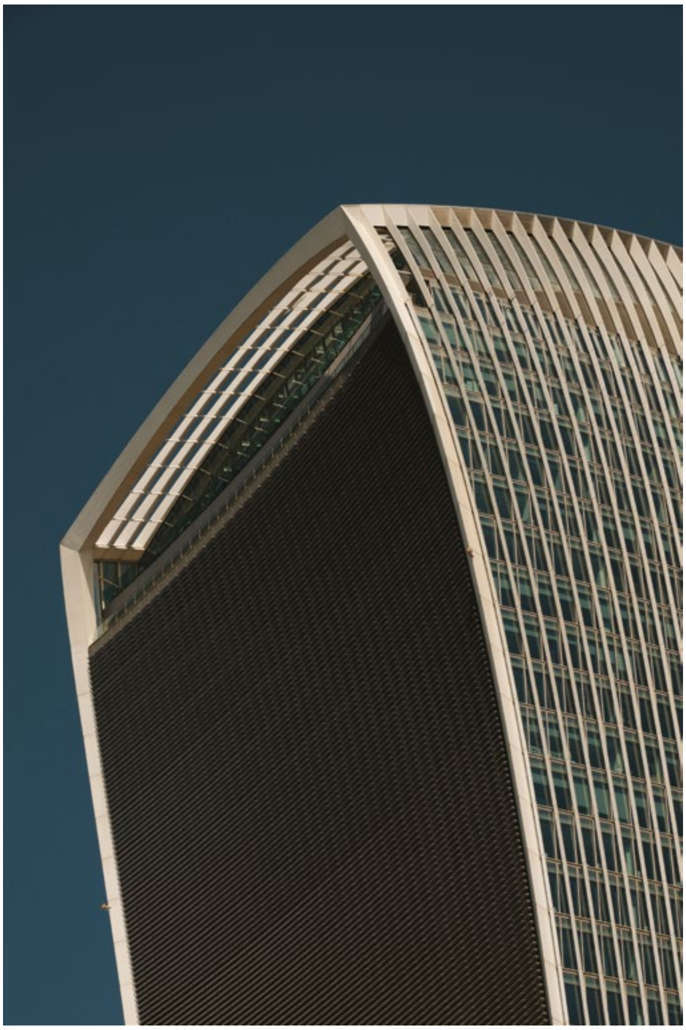
A notable success in this Theme is the development of the Hawkins\Brown Embodied Carbon Calculator, based on research from Yair Schwartz's PhD under the supervision of Dr Ben Croxford and Prof. Dejan Mumovic. This innovative tool provides architects with practical insights to reduce embodied carbon during the design process and won an AJ100 Best Use of Technology 2020 award for its significant industry impact. Schwartz now contributes to teaching across the MEng and MSc programmes.

Funded by Buro Happold, a parallel project, Dynamic Holistic Life Cycle Assessment (PI Mumovic), extends beyond carbon emissions to include energy, water use and wider ecosystem impacts. This project represents a transformative approach to lifecycle assessment, ensuring that decision-making integrates environmental and operational factors from the earliest stages of building design.

The Theme's interdisciplinary approach is further demonstrated by the KTP (Knowledge Transfer Partnership) with AHMM (Allford Hall Monaghan Morris; PI Mumovic), which focused net zero carbon design for mixed-use buildings and the industry-co-funded PhD on energy flexibility in early architectural design. This collaboration aims to embed energy performance considerations into the design process, enabling architects to optimise energy efficiency and sustainability outcomes from project inception.

With the latest revision of the EPBD 2024 requiring GWP assessments for all EU projects from 2030, and UK professional bodies and NGOs collaborating to develop the UK Net Zero Carbon Building Standard, the importance of lifecycle assessment continues to grow. The new standard reflects IEDE policy recommendations on integrating top-down and bottom-up sector-based benchmarks, along with performance outcome verification, to accelerate innovation cycles and enhance accountability for whole-life performance.

Systems Thinking and Transdisciplinarity is a thread that runs through IEDE's Research Themes, providing a structured framework for mapping complex relationships and feedback loops. This approach enables researchers to generate novel insights into the built environment



The Fenchurch Building (The Walkie-Talkie) in the City of London, a skyscraper in London known for its distinctive shape that resembles a walkie-talkie (image credit: Claudio Schwarz / UnSplash)

through transdisciplinary methods. While systems thinking offers a conceptual framework to understand these interconnections, system dynamics, developed in the mid-20th century, provides powerful quantitative tools for stakeholder engagement. Participatory methods, such as interactive simulations, allow researchers to design and test transformative interventions with real-world applications.

Since joining UCL IEDE in 2015, Nici Zimmermann, a Professor of Systems Dynamics, has played a pivotal role in embedding these approaches across the BSEER. As a co-investigator on the third Platform Grant, she has applied systems-thinking and system dynamics tools to topics such as sustainable housing and urban systems. Her work has advanced decision-making processes by engaging stakeholders in modelling and simulations that inform policy and design solutions for complex societal challenges.

A multidisciplinary approach defines this Theme, exemplified by the contributions of Dr Irene Pluchinotta and Dr Gemma Moore, who have collaborated on projects such as CUSSH and the recent Wellcome Trust-funded PAICE project, which focuses on sustainable urban transitions. Dr Pluchinotta, an engineer with dual PhDs in environmental engineering and computer science, brings expertise in systems dynamics, decision analysis and sustainability. Her unique multidisciplinary experience spans three sectors, allowing her to develop sophisticated mathematical models that support participatory decision-making. Complementing this, Dr Moore specialises in participatory stakeholder engagement, integrating co-production and participatory methodologies to address complex challenges. Together, they ensure that systems-thinking approaches bridge academic insights with practical, community-driven solutions for sustainable cities.

The third Platform Grant also reinforced UCL IEDE's industry ties, enabling fellowships, collaborative projects and internships that ensured research outcomes were both actionable and impactful. This collaborative environment has strengthened IEDE's ability to address critical issues, from climate resilience to urban sustainability, using a systems-thinking lens.

Davies, an advocate of the systems-thinking approach, structured IEDE's expertise to span multiple fields of environmental design and engineering. This holistic perspective allows IEDE to connect diverse Research Themes – such as energy, health, acoustics and lighting – into a cohesive agenda that addresses the built environment's most pressing challenges.

By integrating systems thinking and dynamics, IEDE bridges academic disciplines and engages industry and policy makers, ensuring that research not only advances theoretical understanding but also delivers transformative outcomes for the built environment.

UCL IEDE's pioneering research projects have made transformative contributions to The Bartlett Faculty of the Built Environment, featuring prominently in its REF 2021 Impact Case Studies. Despite its relatively small size, IEDE has consistently delivered substantial impact, shaping national and international policies, advancing industry practices and addressing critical environmental challenges.

Findings from the CBES platform grants and related projects informed the UK Climate Change Committee's (CCC's) progress reports and policies on indoor environmental quality, positioning overheating as the second most critical climate risk facing the UK. These insights shaped the UK's National Adaptation Programme and the CCC's Fit for the Future? report, guiding construction practices, occupier behaviour and the use of green spaces to mitigate overheating. In recognition of this impact, Prof. Mike Davies was appointed to the CCC Adaptation Committee in 2018.

UCL IEDE research has defined best practices for healthy and sustainable learning environments, influencing the Priority School Building Programme, the GLA's IAQ initiatives and the Department for Education's (DfE's) BB101 (Building Bulletin 101) on ventilation and thermal comfort. Innovative technologies like PVHR (Passive Ventilation with Heat Recovery), developed with Ventive, have improved air quality for over 8,000 children in 40 UK schools. Findings from air quality monitoring tools, such as the AQ110, have been embedded in CIBSE guides TM61 and TM64, ensuring widespread dissemination across the industry's 22,000 members. In recognition of his school research expertise, Prof. Dejan Mumovic was appointed Scientific Advisor for Climate Change to the DfE in 2023.

UCL IEDE researchers play leading roles in professional organisations such as CIBSE, REHVA (Federation of European Heating, Ventilation and Air Conditioning Associations) and IBPSA (International Building Performance Simulation Association), contributing to the development of guidelines and technical standards, including CIBSE Technical Memoranda TM54, TM57 and TM61–64. Their work influences European Commission health policies and has advanced industry benchmarks for sustainable building performance.

UCL IEDE's Research Themes actively inform teaching at the undergraduate and MSc levels, and about a dozen doctoral research projects are tackling priority topics in each Research Theme. Students gain valuable experience through teaching contributions, and many return as design tutors, ensuring the continuation of UCL IEDE's innovative and practical teaching practices.

Over six decades, UCL IEDE has undergone a 'revolutionary evolution', redefining environmental design to meet global challenges. Since its origins as a key contributor to architecture and environmental engineering, UCL IEDE has grown tenfold, achieving a critical mass of expertise. This transformation has been driven by a culture of mentorship and inclusivity, with half its staff comprising former students and a near 50:50 gender balance among professors.

Adopting a systems-thinking approach, UCL IEDE integrates physical, digital and socioeconomic perspectives to explore the interplay of thermal, respiratory, lighting and acoustic conditions. Methodologies have progressed from empirical and experimental studies to advanced computational simulations that merge big data with experimental research conducted in state-of-the-art labs at UCL East. Through more than 100 funded research projects, the department's work now spans all major built-environment-related UN SDGs, including energy, carbon, water, biodiversity, health, climate resilience and social value creation.

By collaborating across disciplines such as health, design, resource economics and civil engineering, IEDE prepares a new generation of built environment professionals to tackle UCL's six Grand Challenges. At the same time, it champions the transformative role of creativity and social sciences in redefining traditional engineering disciplines, just as UX design takes centre stage in the built environment professions.

Honorary professors, including Prof. Sani Dimitroulopoulou from Public Health England and Honorary Prof. Sarah Bell, former Director of the Engineering Exchange at UCL, ensure that IEDE's research addresses pressing industry and policy challenges, amplifying its impact beyond academia.

With a research portfolio exceeding £30 million and projects worth over £25 million set to launch in 2025, IEDE is poised to lead the next era of environmental design. Its integration of emerging fields such as mental health and climate change places it at the forefront of advancing wellbeing and sustainability in the built environment.

The Here East building, viewed from Parkes Street (image credit: Edward Barrett).

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FLAGSHIP RESEARCH PROJECTS IN 2025

View of the Marshgate building at UCL East, with the Arcelor Mittal Orbit tower, the Olympic Stadium and London in the background, November 2020 (image credit: UCL East, Marketing)

Policy and Implementation for Climate & Health Equity (PAICE)

Call: Advancing climate mitigation policy solutions with health co-benefits in G7 countries
Start date: 1 November 2023
End date: 31 October 2026
Total value: £1.6 million led by UCL

Abstract:
PAICE will inform and evaluate UK Net Zero policies using transdisciplinary approaches to generate and implement evidence. Climate change mitigation policy must consider population health and health equity alongside reductions in greenhouse gas emissions, and would benefit from an integrated, intersectoral approach. We will develop shared priorities with stakeholders, understand current and planned policies, build models to assess their cross-sectoral impact, consolidate a monitoring framework, and evaluate and help accelerate delivery. PAICE brings together experts from four Wellcome-funded projects (CUSSH, SHEFS, Pathfinder Initiative and HEROIC) that have generated evidence on the connections between climate and health in the energy, housing, food and transport sectors. We will: (1) co-develop a programme theory and linked monitoring and evaluation plan, (2) work with the UK Climate Change Committee (CCC) using system dynamics to analyse policy opportunities, (3) build a model of the effects of these policies on population health, health equity and greenhouse gas emissions, (4) apply the findings to the CCC monitoring framework, and (5) use the programme theory to evaluate achievement of processes and objectives. PAICE responds to the opportunity to directly influence national policy development and implementation through the pivotal CCC and by sharing findings with G7 partners.

Affordable and digital solutions to Build the next generatiON of smart EU buildings (BuildON)

Call: HORIZON-CL5-2022-D4-01-03 - Smarter buildings for better energy performance
Start date: 1 May 2023
End date: 31 October 2026
Total value: € 6.7 million

Abstract:
The 2021 EPBD recast underscored the central importance of buildings in driving the energy transition toward an integrated, renewable-based energy system. Smarter buildings will play a key role in supporting both digitalization and decarbonization, ultimately benefiting occupants, property owners, and the wider energy network. Enhancing energy performance and reducing consumption takes on even greater urgency in the context energy independence. In response, the BuildON project seeks to create a highly adaptable, widely applicable solution that delivers intelligent building services. It aims to seamlessly integrate various systems and technologies, fostering the next generation of smart buildings.

The project's will develop and demonstrate a Smart Transformer Toolbox for planning and achieving better energy performance across many building types and varying levels of smart readiness. This will be demonstrated through five real-world use cases. The toolbox will provide cost-effective, easily adaptable, near-market, and simple-to-install SRI-aligned services for continuous Monitoring, Assessment, Prediction, and Optimization (MAPO) of a building's performance. A unified building representation—accessed through a Universal Building API—will hide the complexity of different on-site systems and enable uniform, real-time monitoring and control of energy devices. At the same time, advanced Digital Twins (at Maturity Levels 3 and 4) will allow for detailed simulation and control of a building and its internal systems. The toolbox also includes user-friendly tools to help facility managers and occupants explore, understand, and enhance their buildings' smart functionalities. By providing a cohesive way to engage with building systems, BuildON effectively lays the groundwork for a dynamic "building app store," accelerating the smart transformation of both existing and new buildings.

Child and adolescent Health Impacts of Learning Indoor environments under net zero: The CHILI Hub

Call: UKRI Realising the health co-benefits of the transition to net zero Hubs
Start date: 1 February 2025
End date: 31 January 2030
Total value: £5.5 million led by UCL

Abstract:
The CHILI Hub which will focus on six aspects: Map: We will measure indoor air pollution in classrooms and schools across England and Wales and combine these measurements with measured and estimated outdoor air pollution data. This will help us develop indicators of indoor environments in schools that can be compared between areas. Understand: We will combine these school indoor environment indicators with national data on children's health and education, collected by hospitals, pharmacies and schools in England and Wales. We will research the link between indoor air pollution or heat in schools and children's health and school non-attendance. Model: We will develop combined building and health impact assessment models, which describe the impact of climate change and energy efficient building alterations, on indoor environments in schools. We will use these models to work out how these changes will affect children's health in the future. Test and evaluate: We will evaluate (weigh-up) if existing technology and behaviours to improve the indoor environment support children's health. This will include examining if installation of air cleaning filters affect children's use of health services, and if window opening impact children's comfort in classrooms. Involve: We will work with children, young people and teachers to develop data collection methods to measure the impact of the indoor environment on children's health and education. Engage: We will set up a network of individuals and organisations who work with, or will be affected by making school buildings meet the net zero target. We will work with them to identify and describe any barriers to making school buildings energy efficient. We will work closely with policy makers, schools, parents and carers, and children and young people to ensure our findings improve health and education for all children.

National Hub on Net Zero, Health and Extreme Heat (HEARTH)

Call: UKRI Realising the health co-benefits of the transition to net zero Hubs
Start date: 1 February 2025
End date: 31 January 2030
Total value: £5.5 million led by Oxford Brookes University

Abstract:
Transformative action, at pace and scale, is required to deliver a net zero building stock in the UK by 2050. This will be enormously challenging and is made even more difficult within the context of a changing climate. In summer 2022, the UK experienced unprecedented 40°C temperatures and five heat periods, associated with 3,271 deaths in England and Wales. A future with more intense and frequent heatwaves, that often co-occur with other weather extremes, poses a severe threat to public health. By the mid-2030s, 90% of the UK's housing stock may be susceptible to overheating. Despite this, UK Building Regulations currently do not require buildings to address future overheating risks driven by a warming climate. While Net Zero measures such as improvements in building thermal performance can reduce heating demand, there is risk of summertime overheating if suitable adaptation measures are not incorporated. Vulnerable populations (e.g., persons with chronic conditions and disabilities, older people, pregnant women, preschool children) and those in insecure housing, confined environments or experiencing homelessness all face a heightened risk during hot spells. Challenge the project addresses: The UK urgently needs to deliver vital climate, health and equity actions which affect homes of different tenures and multifunctional residential environments, including care settings, hospitals and prisons. The need for effective delivery that achieves net zero, maximises co-benefits and minimises unintended consequences for vulnerable communities in these settings is the overarching challenge that the Hub will address. Our hub is designed to address the 'Extreme weather' challenge area, interpreted here as heat extremes and co-occurring events (flooding, drought, wildfires, air quality). Aims and objectives: Aim: HEARTH aims to assess and realise the co-benefits of the net zero transition and the reduction in health risks associated with extreme heat for vulnerable

communities for whom evidence is lacking. We will achieve this through co-production of novel evidence-based knowledge, evaluation frameworks and tools, and provision of actionable, high-impact solutions. We will focus on interventions in the built and associated natural environments that are affected by net zero policies and their related health co-benefits, for which short (now-2030), medium (2030-2050) and longer-term (2050-2100) climate timescales are relevant. Objectives: Produce new high-resolution weather and climate scenarios to assess extreme heat events and co-occurring hazards considering a range of climate mitigation pathways including net zero futures. Quantify disparities in heat exposure experienced by high-risk groups in the outdoor environments of vulnerable settings across five distinct UK locations. Empirically measure physical and mental health impacts and inequalities arising from indoor heat exposure in high-risk groups residing in homes, multi-functional residential environments, and healthcare settings. Evaluate the health, equity and economic impacts of existing climate change adaptation and mitigation measures, including important co-benefits/disbenefits and trade-offs. Co-develop and evaluate a range of new health-focused climate change adaptation and mitigation solutions. Using a systems approach we will address trade offs and unintended consequences. Applications and benefits: We will collaborate with our 32 Project Partners from the public, private and third sectors and utilise existing climate-health initiatives to co-produce new evidence, metrics, decision support tools, and actionable net zero heat-resilience strategies at various spatio-temporal scales to inform and help deliver policy. By developing solutions for heat vulnerable communities, those most susceptible to heat will benefit, and the burden on health care services will be reduced.

Indoor Habitability during the Transition to Net Zero Housing Hub (INHABIT)

Call: UKRI Realising the health co-benefits of the transition to net zero Hubs
Start date: 1 February 2025
End date: 31 January 2030
Total value: £5.5 million led by University of Birmingham

Abstract:
To meet its legally-binding target of achieving net zero emissions of greenhouse gases (GHG) by 2050, the UK must eliminate GHG emissions from homes. This enormous task involves retrofitting—the process of upgrading the energy efficiency—of the 29 million homes. These retrofits will significantly change indoor environments, bringing health co-benefits by improving home warmth during the winter and providing protection against harmful outdoor air pollutants. However, if not done properly, these modifications can trap indoor air pollutants and moisture, deteriorating indoor air quality and causing issues such as damp/mould. These conditions can adversely affect health and wellbeing, particularly for the most vulnerable in society, such as older people and those with pre-existing conditions like asthma. An opportunity and challenges: Retrofitting the UK's homes will require a substantial investment—estimated at £250 billion by 2050. This offers an unprecedented opportunity to enhance environmental and socio-economic outcomes, including public health improvements and reduced inequalities. However, our current lack of scientific knowledge and tools hampers our ability to fully capitalise on this potential. Specifically, we lack understanding of how retrofitting impacts the indoor environment and health in real-world scenarios and we do not have comprehensive tools to assess both positive and negative health impacts of retrofit options. Furthermore, our insights into the complex interactions among the indoor environment, health, inequalities, behaviours, and regulatory and financial frameworks are limited. The INHABIT Hub has been specifically established to tackle these complex challenges. Aims and Objectives: The INHABIT Hub aims to produce scientific evidence and policy-relevant solutions to realise the health co-benefits of the UK's net zero transition in housing. Our main objectives

include: Establishing and growing a transdisciplinary hub to become an International Centre of Excellence that pioneers the improvement in indoor environments and health as the housing sector transitions to net zero. Developing a systems understanding of retrofits' impacts, through observations and modelling, focusing on indoor environment, health and inequalities to promote health-centred actions. Creating a collaborative learning space to boost stakeholders' and researchers' skills in transdisciplinary research and net zero delivery. Co-producing example retrofitting projects that integrate net zero considerations with health and address inequality. Applications and benefits: Co-production with stakeholders is core to our vision, enabling us to deliver policy-relevant knowledge, tools and metrics. That is why we have partnered with a diverse group of stakeholders, including 14 local/regional authorities, 4 housing associations, and 3 businesses, and world-class researchers from 11 organisations. Through workshops and online meetings, we have collaboratively shaped our research priorities. The hub will leverage our significant investments, such as those from the West Midlands Combined Authority's "Net Zero Neighbourhood" initiative. These projects will enable real-world studies such as monitoring indoor environments and health in actual retrofit homes and applying co-developed systems understanding and models in actual retrofitting projects. The insights obtained will enhance the capabilities of local authorities, housing associations, businesses, and other net zero delivery providers to maximise health benefits while meeting urgently-needed net zero targets. Moreover, our work will also yield broader societal benefits, including healthier indoor environments, lower healthcare costs, reduced energy bills, and improved social equity.

Accelerating Resilience and Climate Adaptation of Domestic Environments for vulnerable populations (ARCADE)

Call: NERC Maximising UK adaptation to climate change research projects
Start date: 31 December 2024
End date: 30 March 2027
Total value: £1.6 million led by UCL

Abstract:
Climate change will cause hot weather to become more frequent and intense, which will put human health at risk. The UK has been experiencing more heatwaves lately, including a record-breaking heatwave in 2022 where temperatures hit 40°C. This resulted in more than 3,200 excess deaths in England and Wales. The impact of climate change on human health depends on factors like exposure, vulnerability, inequity, and efforts to address climate change. Studies have found a strong connection between high outdoor temperatures and increased deaths and illness. Older adults and those with health conditions like heart, lung, and neurological problems are most at risk. As the population in the UK gets older, an increased number of older adults will face the risk of heat-related health issues. To mitigate the adverse health effects of heat exposure, we need to consider both outdoor and indoor environments. In cities, Urban Heat Islands can increase heat exposures, underscoring the significance of local urban climate conditions for public health. The indoor environment also greatly affects how people are impacted by heat-related problems as most people, especially older and vulnerable individuals, spend most of their time indoors in different types of housing. In the UK's pursuit of Net Zero emissions, homes are being upgraded to be more energy efficient and reduce winter fuel poverty. While these upgrades can benefit health, it is crucial to avoid indoor overheating, which could harm vulnerable groups disproportionately. Immediate and ongoing action involving stakeholders, particularly those with relevant experience, is essential to effectively address and prevent heat-related risks in the future. The ARCADE project aims to assist decision-makers to protect vulnerable individuals in the UK in adapting to climate change within

their homes, with a particular focus on older individuals and types of housing that have been less studied to date. The project will examine various residential settings, including retirement villages and social housing, to understand how people are affected by heat both indoors and outdoors. It involves experts from different fields (built environment, health, systems thinking) in close collaboration with policymakers, government agencies, healthcare professionals, the construction industry and innovators, working together to address these critical issues. We will build on existing knowledge from previous projects, and use a mixed methods approach to complement it with new evidence. We will monitor the indoor environment and survey occupants in selected buildings to gauge the impact of heat on them. We will also simulate the indoor environment in these buildings and the outdoor environment near them using computer modelling. This will help us assess the vulnerability of the residents to heat-related issues, now and in the future, under different climate change scenarios. We will develop tools to evaluate the heat risk and model heat-health impacts using existing statistical data, and also assess the effectiveness and costs of different overheating mitigation measures, both using models as well as interventions (ventilation, shading etc.) in real buildings. Through workshops with key stakeholders, we will help them improve decision-making to maximise the climate change adaptation of older, heat vulnerable populations. Improving understanding of how various groups perceive climate change and heat-related risks for older individuals can pave the way for modifying beliefs and policies. By integrating these insights into current policies, decisions can better address the needs of older populations residing in heat-prone residential areas.

NIHR-Climate Change and Health Security-Health Protection Research Unit

Start date: 1 April 2025
End date: 31 March 2030
Total value: £5.5 million

Abstract:
Our health is greatly influenced by our environment. Significant changes to our environment, including climate change, threaten the foundations of a healthy society. Recent record-breaking temperatures in the UK emphasise the urgent need to better protect the public from the health threats associated with climate change. Our vision for the Health Protection Research Unit (HPRU) in Climate Change and Health Security is to produce the research evidence needed to enable the UK Health Security Agency (UKHSA) to protect the health of our communities in the UK against the effects of climate change. We aim to do this by carrying out world-leading research on the health impacts associated with key climate hazards and demonstrating what type of actions and intervention measures help to reduce risk. Doing this properlyrequires good evidence of what may influence someone's risk (such as age and medical history) and detailed knowledge of the ways in which climate can affect health. This can range from direct impacts such as illness associated with exposure to hot weather to indirect processes such as climate change affecting the spread of pathogens that cause infectious diseases such as salmonella. By building on the successful partnerships and research developed in the previous phases of the HPRU, including with members of the public, we are uniquely placed to address these challenges. To generate the evidence needed to support UK public health policy and practice on climate change, we will develop new research methods to measure the health impacts associated with climate change and identify people most at risk. We will measure the health impacts associated with extreme weather such as heat-waves. There is currently very little evidence from the UK on how such climate hazards affect mental health, and as a result guidance for mental health protection is limited, so the work will include measurement of climate impacts on a range of mental health conditions. We will also conduct research on climate-sensitive infectious diseases.

Both mental and physical health impacts associated with climate change will be assessed in outdoor and indoor settings. We will measure how hot temperatures can get in peoples' homes as well as in places with many vulnerable individuals, such as hospitals and care-homes. We will also estimate likely future health impacts if the climate continues to change. In addition, we will measure the health and economic implications of different interventions designed to protect against climate change. This information will help enable policymakers to choose between different policies, including policies in other sectors such as housing and transport since they could also affect public health. We will work closely with local authorities to better understand factors that lead to more effective interventions, including public acceptability. We will work alongside UKHSA and other key stakeholders to test different adaptation strategies at a local and national level. We will also continue to work closely with members of the public to help design our research and to share research findings.

Research Capital Investment Funding 2025

Repurposing of two double environmental chambers in Here East to provide greater accessibility, increased testing and environmental control capabilities and to enhance interdisciplinary activities (£264,000): This upgrade of IEDE's environmental chambers will enable advanced research across the Bartlett, particularly in airtightness, moisture buffering, and robust building design under future climate scenarios. Humidity and pressure controls will allow testing of material response, informing strategies for durability and energy efficiency. The facility will permit new studies on climate impacts on people, focussing on healthy individuals, with or without disabilities, and cognitive function.

Investigators: Dr Valentina Marincioni, Dr Edward Barrett, Jalal Ahmed, Prof Sanjay Sisodiya, Prof Hector Altamirano-Medina

Measuring the Impact of Light on Health (£63,746.30): New research on the beneficial impact of the near infrared (NIR) on various heath parameters such as colour discrimination and metabolism, has potentially population wide impact, given the increase in the prevalence of diabetes. However, effects have largely been tested in term of medical treatments rather than exposure via the built environment. This equipment supports the reporting of physiological outputs including melatonin, cortisol, blood sugar levels, and eye tracking.

Investigators: Dr Jemima Unwin Teji, Ruoxi Yin, Dr Umasuthan Srirangalingam, Cephas Bhaskar, Simone Bonavia, Dr Annegret Dahlmann-Noor, Prof Glen Jeffery

A Modular system: Multi-for integrated health and wellbeing risk assessments across the indoor and outdoor continuum environmental wearables for large scale characterisation of personal exposures (£173,463): Environmental Quality (EQ) affects health and well-being in buildings and cities, as well as approaches to Net Zero. Advances in monitoring devices enabled measurement of personal exposure, demonstrating the importance of considering exposure across the 24-hour cycle (and over the life course), and across the indoor-outdoor continuum. This modular system allows high precision characterisation of physiological parameters: peripheral skin temperature, electrodermal activity, blood oxygen, and sleep detection, respiratory rate, pulse rate variability and EDA/skin conductance level.

Investigators: Dr Mandana Khanie, Prof. Marcella Ucci, Prof. Wilson Duncan, Prof. Andy Hudson-Smith, Prof Kerstin Sailer, Assoc. Professor Fiona Zisch, Prof. Sonia Ghandi, Prof. Kate Jones, Dr Francesco Alleta

Aerial view of London's urban landscape – a small part of the complex system in which climate change mitigation, health, and health equity intersect. Policy and Implementation for Climate & Health Equity (PAICE) project (image credit: UCL Media Services)

TEACHING

2.1 MSc ENVIRONMENTAL DESIGN AND ENGINEERING

2.2 MSc LIGHT AND LIGHTING

2.3 MSc HEALTH, WELLBEING AND SUSTAINABLE BUILDINGS

2.4 MSc SMART BUILDINGS AND DIGITAL ENGINEERING

2.5 MEng ENGINEERING AND ARCHITECTURAL DESIGN

2.6 BSc/MEng SUSTAINABLE BUILT ENVIRONMENTS, ENERGY AND RESOURCES

2.7 ADVANCING TRANSDISCIPLINARY ARCHITECTURE AND ENGINEERING EDUCATION

2.8 SUPPORTING THE CASE FOR BSc/MEng SUSTAINABLE ENVIRONMENTS, ENERGY, RESOURCES

Revolutionary Evolution

Are you interested in making our buildings towns and cities better places to live? Do you want to make them more sustainable, healthier and more efficient and productive? Our degrees explore the interactions between the built environment and health, human wellbeing, productivity, energy use and climate change, preparing graduates with the skills needed to build their career is sustainable building design and engineering.

MSc ENVIRONMENTAL DESIGN AND ENGINEERING

(established: 1978, designed for 60FTE students, duration: 12 months, CIBSE Happold Brilliant Award) Peter Raynham, Prof. Peter Boyce, Dr Jemima Unwin Teji

About this degree

In the face of environmental crises, adapting the built environment to create healthier, more sustainable buildings, towns, and cities is more crucial than ever. UCL's Environmental Design and Engineering MSc equips you with the skills to address these critical issues, teaching you to apply innovative and sustainable approaches for efficient building design and operation through integrated design and engineering. The course leverages the expertise of specialists from leading companies to ensure the content remains industrially relevant. Upon graduation, you will join our extensive network of alumni who have been driving change in building design and construction for the past 46 years.

During your degree you will:

Explore the fundamentals of energy demand and the consequences on the design, engineering and regulatory processes taking place in the built environment.

Examine how buildings and the built environment impact people's health and wellbeing by learning about Indoor Environmental Quality and applying knowledge to existing buildings to assess the effects of indoor air quality, and thermal, acoustic, and visual comfort.

Learn how to design for the climate emergency gaining key skills in using passive design, natural and mechanical ventilation systems, solar heating and cooling and addressing embodied carbon.

Gain expertise in building performance simulation and modelling tools to inform the design of sustainable buildings.

Learn about net zero carbon design and engineering, evaluating the whole life carbon emissions of building services systems to the whole life carbon emissions of buildings.

Gain hands on experience applying laboratory and field experiment techniques using state-of-the-art facilities to explore the energy and environmental performance of real buildings.

Explore your own specialist interests by choosing optional modules spanning advanced building simulation, retrofit, indoor air quality, acoustics, systems thinking, energy systems modelling and more.

Who this course is for

This MSc is ideal for recent graduates and early to mid-career building professionals seeking to enhance or pivot their careers towards sustainable and environmental design and engineering. It is particularly suited for recent graduates with backgrounds in architecture, engineering, physics, or other building industries or environment-related fields. For early and mid-career professionals, this degree offers the opportunity to deepen your expertise in sustainability, environmental impact, energy efficiency, and health issues related to buildings.

Accreditation

This course has been accredited as suitable further learning to meet the academic requirement for Chartered Engineers (CEng) by the Chartered Institution of Building Services Engineers (CIBSE) and the Energy Institute (EI).

MSc LIGHT AND LIGHTING

(established 1987, designed for 30FTE students, duration: 12 months)

About this degree

From gas lamps to LEDs, as technology has progressed, the lighting industry has become increasingly specialist. UCL's Light and Lighting MSc is designed to provide you with a comprehensive knowledge base and skill set to build a successful career in the lighting profession, whether as a lighting designer, luminaire manufacturer, or as part of an architectural or engineering firm. As a student, you will gain in-depth expertise in the science of light, lamp and luminaire technologies, and the impact of light on architectural form and human response to both daylight and artificially lit spaces. This knowledge will equip you with the vision to design beautiful lit environments that promote user wellbeing and the skills to ensure they are successfully engineered. You will join a global cohort of students studying pioneering sustainable approaches to lighting design, operation and research.

During your degree you will:

Study the fundamentals of lighting, including natural daylight, lighting technologies, design calculations, and the human response to lit environments.

Utilise advanced design techniques to produce conceptual and detailed lighting designs and luminaire product designs.

Be taught mathematical models and physical concepts for illumination, applied to the reality of the lit environment.

Learn how to design a lighting control system that meets people's needs in different environments.

Gain experience using computational design tools used in the lighting and architectural industry such as Rhino 3D, Grasshopper, Ladybug/Radiance and DIALux.

Explore the evolution of lighting design and innovation over time, giving the historical context for lighting design practice in the present day.

Understand essential lighting practice, regulations and standards required for lighting designers.

Delve into current research in lighting, sustainability, health and wellbeing.

Who this course is for

This course is ideal for recent graduates as well as early to mid-career professionals seeking to expand their knowledge in the field of lighting. Individuals passionate about lighting are encouraged to apply. While applicants typically come from backgrounds in architecture, interior design, industrial design, engineering, science, arts, and theatre, we welcome all prospective students with an interest in lighting.

Accreditation

The Light and Lighting MSc has been accredited by the Chartered Institute of Building Service Engineers (CIBSE) as meeting the further learning requirements for Chartered Engineer (CEng) status. The course is recognised by the American National Council on Qualifications for the Lighting Professions - NCQLP, making it easier for students achieve LC Certification.

MSc HEALTH, WELLBEING AND SUSTAINABLE BUILDINGS

(established in 2017, designed for 30FTE students, duration: 12 months)

About this degree

Health, Wellbeing and Sustainable Buildings MSc was launched in response to the demand for a new generation of experts to drive the health and wellbeing agenda in the built environment. The convergence of the sustainability, health and wellbeing agendas has led to the emergence of a more holistic, human-centred approach to design, and made health and wellbeing an increasingly influential research area. You will be taught by multi-disciplinary research-active leaders in the field and have opportunities to network with and learn from industry and practice-based experts, to develop your understanding of commercially applicable, research-oriented tools and approaches.

During your degree you will:

- Acquire the skills to address health, wellbeing, and human performance in the design, assessment, and operation of buildings, including new builds, retrofits, and existing structures.
- Understand the interactions between human-centred outcomes and sustainability issues and explore the challenges of balancing multiple outcomes.
- Learn how social and built environment factors impact health, wellbeing, and performance across different spatial scales, from individual buildings to urban environments.
- Innovate and design solutions and operational strategies for the remediation or alleviation of health and comfort challenges within buildings.
- Enhance critical thinking and expertise in modelling, monitoring, and design approaches, and learn to sustainably implement health and wellbeing across various disciplines and building types.
- Use a variety of methods and tools to evaluate and predict the impact of building and built environment features on health, wellbeing, and performance.
- Gain a deeper understanding of individual and social factors influencing building and spatial use, and the built environment positively affects users' physical and mental health, and boosts productivity.

Who this course is for

The Health, Wellbeing and Sustainable Buildings MSc is interdisciplinary and attracts students from a range of disciplines including architecture, engineering, interior architecture and design, physics, and other related disciplines, including the built environment, geography, public health and environmental psychology who wish to gain further training in the field. We also welcome your application if you are an early or mid-career professional in the built environment, public health, environmental psychology, or other relevant fields wishing to deepen your skills and knowledge.

Accreditation

The Health, Wellbeing and Sustainable Buildings MSc is accredited as further learning for Chartered Engineers (CEng) by the Chartered Institution of Building Services Engineers (CIBSE).

MSc SMART BUILDINGS AND DIGITAL ENGINEERING

(established in 2018, designed for 30FTE students, duration: 12 months)

About this degree

The world is rapidly evolving, and so are our buildings. With advancements in digital tools for building performance analysis and technologies like the Internet of Things, we now have unparalleled data insights and tools to innovate how buildings are designed and operated. This course provides a forward-looking perspective on the digital transformation of Building Services Engineering, emphasising sustainable building design and the creation of smarter, more efficient buildings that prioritise occupant wellbeing.

During your degree you will:

Explore scientific principles underlying the design and operation of buildings and their systems.

Gain hands-on experience with data-driven approaches to enhance building operations. Working with a series of case studies you will be supported in using machine learning algorithms and tools.

Apply modelling techniques to optimise the operation of efficient building systems as a part of the integrated system of building fabric, building space, occupants, building services and controls.

Gain practical experience with industry-standard tools such as EnergyPlus and DesignBuilder, and become familiar with modelling languages like Modelica, applying these skills in project work and real-world challenges.

Learn and utilise Python to develop and apply advanced analytical methods, supporting data-driven decision-making in building design and operation.

Develop and interrogate digital building twins, and understand how these can support better insights into building performance and occupant comfort.

Gain insight into how building systems impact occupants and the sustainable operation of buildings, with a strong emphasis on decarbonisation within the construction industry.

Participate in a field trip and visit the latest smart buildings in London and beyond to explore real-world challenges and best practice.

Tailor your studies to your interests by selecting specialist optional modules in areas such as energy systems modelling, indoor air quality, urban building energy modelling, building acoustics, lighting, retrofit, and more.

Engage with industry experts to solve real-life problems, preparing for a career at the forefront of this emerging discipline.

Who this course is for

This course is ideal for recent engineering graduates with a strong quantitative background and a keen interest in understanding novel modelling techniques and building systems to drive engineering innovation and sustainability in the built environment. Additionally, this highly technical degree is relevant for early and mid-career professionals seeking to expand their technical skills and knowledge, keeping up with the latest developments to build their career prospects in the field.

Accreditation

This MSc has been accredited as suitable further learning to meet the academic requirement for Chartered Engineers (CEng) professional registration by the Chartered Institution of Building Services Engineers (CIBSE).

MEng ENGINEERING AND ARCHITECTURAL DESIGN

(established in 2017, designed for 60FTE students per year, duration: 4 years, CIBSE Happold Brilliant Award)

About this degree

This four-year programme has been designed in close collaboration with industry leaders to combine the major disciplines of architecture and engineering of the built environment and prepare graduates to be future industry leaders. Your learning is predominantly design studio-based, and incorporates extensive use of fabrication workshops, engineering laboratories and London as a living lab, with a strong focus on engineering and architectural design and research-based learning. Methods include lectures, seminars, tutorials, individual and group work, site visits, field trips, workshops, laboratories, design reviews, and e-learning.

Accreditation

This fully accredited programme (ARB/RIBA Part 1, JBM and CIBSE) places creativity, design and architecture at the centre of a robust engineering education. This omni-disciplinary degree gives you the chance to understand and develop architecture (ARB/RIBA Part 1) with advanced design methodologies whilst learning how cutting-edge, sustainable proposals are augmented, calculated and resolved through civil (JBM) and building services (CIBSE) engineering.

BSc | MEng SUSTAINABLE BUILT ENVIRONMENTS, ENERGY AND RESOURCES

(established in 2022, designed for 60FTE students per year, duration: 3 years BSc, and 4 years MEng)

About this degree

The time to act on climate change is now. We need a new generation of experts with the skills to make our buildings, towns and cities more sustainable, healthier places to live. UCL's Sustainable Built Environments Energy and Resources BSc and MEng is a unique solution-oriented undergraduate degree that combines every aspect of sustainability, from social and environmental science to resource economics and engineering, to give you the skills needed to take decisive climate action and help build a sustainable future.

During your degree you will learn:
Social, environmental and economic theories, and how these can be used to address climate change, achieve net-zero emissions, and improve health and wellbeing in the built environment.

How to use data analysis, modelling and advanced decision-making processes to design, construct, operate sustainable buildings, neighbourhoods and cities.

How to use important digital tools and software used in sustainability to provide creative solutions to real-world problems.

Essential maths and statistics required to work in sustainability, learning through real-life examples with additional support provided.

The key challenges facing sustainable built environments, including heritage, health and culture, and how to overcome them.

Leadership, critical thinking, communication, problem-solving and other employable transferrable skills.

Beyond lectures and workshops, you will get hands-on experience applying your theoretical knowledge to real-life sustainability issues in our 'Sustainable Buildings Challenges' and 'Sustainable Cities Challenges' modules.

Depending on your ambitions, you can take the course as either an MEng or BSc (Hons).

Students on the MEng route will wish to become sustainability engineers. They will study for four years, gaining the same comprehensive understanding of sustainability issues in the built environment as BSc students as well as taking additional engineering-focussed modules. We are actively seeking accreditation so MEng students can apply to become Chartered Engineers once they have completed their studies.

Students on the BSc (Hons) route will be motivated to gain a comprehensive understanding of sustainability issues in the built environment ready to kick-start their career in a range of different sectors concerned with sustainability. BSc students will study full-time for three years.

If you are unsure of which pathway is right for you, you can apply for either route and at the end of the second year you will have the opportunity to change.

Accreditation

This programme is designed to be fully accredited CIBSE programme in 2026 at the end of the first 4 years cycle (as per Engineering Council UK timeline).

ADVANCING TRANSDISCIPLINARY ARCHITECTURE AND ENGINEERING EDUCATION: REVOLUTIONARY REVOLUTION

Elizabeth Cooper, Sonja Oliveira, and Dejan Mumovic

There is wide recognition in policy, practice and higher education that complex climate change challenges cannot be fully addressed without highly integrated multidisciplinary knowledge and ability. This is especially critical in the built environment. The purpose of this article is to discuss approaches through which educational and practice needs of a new multidisciplinary built environment professional are being considered. The article builds on a prior study by the authors involving a UK case study drawing on the developmental process involved in creating and running a novel highly integrated MEng course and begins to assess the outcomes of the first cohort that completed the programme. The insights help define the approaches that underpin development of a multidisciplinary course, evaluate the outcomes, and articulate the potential competency criteria needed for a new design professional. These criteria will aid future development of engineering professions and ways professional bodies accredit educational provision.

Keywords - Built environment, Design, Engineering, Higher Education, Multidisciplinary

Introduction

There is established recognition in international policy that multidisciplinary knowledge and competencies are critical in addressing growing complexity of climate change and carbon emissions challenges (Friedlingstein et al., 2022). The need for multidisciplinary approaches is particularly significant in the built environment context, a key contributor to carbon emissions globally (Friedlingstein et al., 2022). This recognition has led to an increasing understanding in education and practice that solutions may lie not only in more effective integration of built environment multidisciplinary teams but also in the educational development of a new kind of built environment professional (Butt & Dimitrijević, 2022; Nguyen & Mougenot, 2022).

In the higher education (HE) context, multidisciplinary approaches are seen as a classification of interdisciplinarity with interdisciplinarity seen as the ‘integration of knowledge drawn from diverse disciplines to address problems that cannot be solved by one discipline’ (Van den Beemt et al., 2020). Though there are emerging courses in the built environment that promote integration of different disciplinary domains such as architecture and structural engineering, architecture and building services engineering and more recently architecture, structural and building services engineering, there have been few accounts of their developmental approaches (Oliveira et al., 2022), and a paucity of published evaluations of the educational or career outcomes. It is widely recognised that identifying pathways to multidisciplinary education remain challenging. A recent review carried out by Van den Beemt et al. (2020) on approaches to interdisciplinary education in engineering suggests that developing both multi and interdisciplinary skills demand a different type of pedagogy and ‘teaming experiences’ that facilitate new ways of learning. Their review also argues for a greater understanding of resources needed as well as barriers to wider development of interdisciplinary education including awareness of the institutional challenges involved.

Research in architecture and engineering education has mostly approached the issue by analysing ways to achieving multidisciplinary curricula largely through either incorporating sustainability or enabling design-studio and/or project-based learning delivered by multiple disciplines (Oliveira et al., 2022). The purpose of this paper is to discuss the development and early implementation of educational and practice needs of a new multidisciplinary built environment professional drawing on authors' prior case study of a UK MEng Course (Oliveira et al., 2022). The discussion has benefits to both higher education providers and practitioners in helping articulate the potential competencies and needs of a future built environment professional, and the underpinning processes that may shape its delivery.

Methodological approach and case

This work builds on the empirical case study explained and discussed in the authors' recent paper (Oliveira et al., 2022). The methodological approach of this previous work involved narrative synthesis including reflection and dialogue of a prior empirical case study as well as thematic review of the literature (Lisy & Porritt, 2016). A review of the development processes for the UCL MEng Engineering and Architectural Design course, with the primary focus being on understanding how the multidisciplinary content and delivery mechanisms developed during the initial stages of the course development, was conducted. In addition to extensive documentary analysis, the case study also involved holding interviews with educators and industry advisors on the curriculum design process. The course was developed to provide a fully accredited pathway for chartered engineer status through JBM and CIBSE, with expanded attributes in architectural design. These requirements informed the initial criteria through which discussions developed amongst the curriculum design team. The curriculum design team involved expertise from multiple departments representing diverse disciplines including academics from The Bartlett School of Architecture, the UCL Institute for Environmental Design and Engineering and the Department of Civil, Environmental and Geomatic Engineering as well as leading industry experts.

The course development also included discussions of facility provision and the site for course delivery was a critical aspect of joining up disciplinary thinking and developing the multidisciplinary ethos of the course. The following section describes the empirical setting, the rationale for the course as viewed by its creators and the ways future graduates and their experiences were conceived.

The rationale for the course – a paradigm shift

The UCL team's contention in developing the course was rooted in their view that 'grand challenges facing society, and indeed the planet i.e., sustainability, well-being, changing climate, and intercultural interactions, all implicate the built environment'. The course was described to be aimed at creating a novel interdisciplinary workforce, and network, of creative professionals each with complimentary knowledge and skill in both engineering and architectural design, who are better equipped to exploit the opportunities afforded by new technologies and methods. The need for this programme was described by its creators to be also evidenced in the paradigm shift that is taking place in the way our built environment is designed, procured, constructed, and regulated.

The rationale for launching this new programme also related, according to the team developing it, to UCL's location in London and its unique proximity to many of the world's leading consultants operating in the forefront of the field such as, AKT II, Arup, Foster and Partners, Fielden & Clegg, Buro Happold, Price and Myers, and Laing O'Rourke. The programme is based at new facilities at Here East, Hackney Wick which house a sequence of multi-functional and adaptable large-scale spaces. These extend from 1) public/exhibition/foyer/studios, to 2) a large collaboration hub for demonstrations/assemblies/ and gatherings of variable scale, through to 3) a large volume fabrication space for large scale manufacture and assembly, and 4) a large research hub for dedicated projects at an advanced level, including environmental chambers. The ensemble is promoted to provide a state of the art, world-class facility with unrivalled transparency and ease of engagement between the constituent parts of learning, research, and enterprise. Occupants are said to be provided with an entirely novel environment that is part gallery and archive, part auditorium and theatre, part studio and office, part laboratory and factory, and part social generator, all in one envelope.

Student experience and teaching delivery was described to be centred on a combination of the design studio model that underpins ARB/RIBA validated programmes with engineering problem-based learning excellence. This was viewed to be a unique mix, placing creativity and design at the centre of engineering education, to challenge conventional models, allowing students the opportunity to understand and develop advanced design methodologies whilst acquiring expertise on how they are augmented and resolved through engineering knowledge. The course development team also initially described how graduates needed to develop the confidence, knowledge, expertise, and creative propositional abilities to undertake the critical first steps of a project including brief development and design in a context of significant uncertainty, and to advocate their designs and engage in robust critical interdisciplinary discussion as they evolve. The course structure is graphically summarised in Figure 1 and an outline of the core and elective modules is provided in Table 1. Rooted in discussions of developing key knowledge and ability were initial thoughts on key competencies needed.

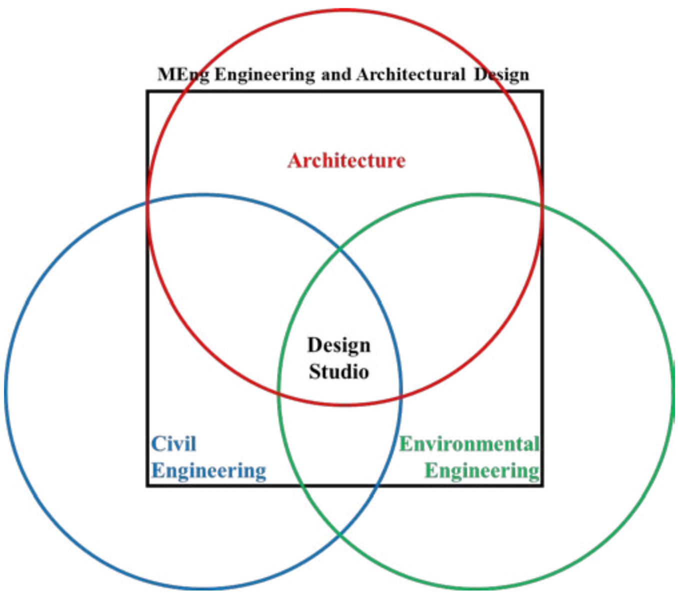

Figure 1 Course structure diagram (Oliveira et al., 2022)

Approaches to initial thinking on key competencies for multidisciplinary built environment design professionals

The course is intended to provide an environment where completing graduates will:

Be prepared for a professional life in the integrated design of the built environment

Have the educational competencies for corporate membership of a relevant professional institution such as the ICE, IStructE or CIBSE

Practically apply fundamentals to real-world scenario to enable rich and divergent analysis and development

Critically apply appropriate tools and processes to expeditiously deliver advanced and pertinent propositions

Have the tools and confidence to bridge and unify previously disparate disciplines

Develop a study, research and work principle that is both conceptually and practically interdisciplinary Be equipped with the necessary skills and expertise to discover and grow their own design and engineering vision within a diverse culture and fast-changing environment

Have knowledge and skills to authoritatively challenge status-quo and develop new paradigms

Lead in meeting the national and international demands for productive and environmentally effective built environments

Have the acumen and knowledge to undertake further research and scholarly activity

Be inspired, prepared and fully supported individuals with opportunity to fulfil their personal goals, their intellectual and creative potential

Integrated master's degrees (often denoted MEng) accredited for the purpose of CEng registration need to demonstrate an emphasis on developing solutions to problems using new or existing technologies, through innovation, creativity, and change. The integrated master's is promoted to go beyond the outcomes of accredited bachelors (honours) degrees to provide a greater range and depth of specialist knowledge, within an authentic environment, as well as a broader and more general academic base. As such the development team drew on the Accreditation of Higher Education Programmes (AHEP4) learning objectives, noting how they provide a sharper focus on inclusive design and innovation, and the coverage of areas such as sustainability and ethics. The coverage of equality, diversity and inclusion is also noted to be further strengthened to reflect the importance of these matters to society as a whole and within the engineering profession.

Courses like this, according to the team developing them, were seen to provide a foundation for leadership and innovative engineering practice. Graduates from an integrated master's degree such as this were intended to achieve interdisciplinary learning outcomes, possessing a broad and coherent body of knowledge including mathematics, natural science and engineering principles, and a proven ability to apply that knowledge to analyse and solve complex problems. Graduates need to be able to select and apply quantitative and computational analysis techniques in the absence of complete data, discussing the limitations of the methods employed.

Table 1 Summary outline of the course structure

Year 1	Year 2	Year 3	Year 4
Core Module 1 History and Theory of Engineering & Architecture	**Core Module 8** Structural and Foundation Analysis and Design	**Core Module 13** Mechanics of Buildings	**Elective Module 1** (Range of options)
Core Module 2 Mathematical Modelling and Analysis I	**Core Module 9** Advanced Mathematical Modelling and Analysis	**Core Module 14** Sense, Sensing and Controls	**Elective Module 2** (Range of options)
Core Module 3 Building Physics and Energy	**Core Module 10** Urban Physics	**Core Module 15** Practice and Project Management	**Core Module 18** MEng Dissertation
Core Module 4 Building Physics and Environment	**Core Module 11** Environmentally Responsible Building Systems	**Core Module 16** Making Buildings	**Core Module 19** Design Practice 3: Vertical Design Units
Core Module 5 Materials Mechanics and Making	**Core Module 12** Design Practice I: Design Studio	**Core Module 17** Design Practice 2: Vertical Design Units	
Core Module 6 Design Make Information			
Core Module 7 Design Make Live			

With an appreciation of professional engineering practice and ethics, graduates were also expected to be commercially aware and able to apply their knowledge and skills to design, deliver and evaluate innovative new products or services to meet defined needs using new or existing technologies.

Whilst the above section explained the ambition and initial thinking conveyed by the development team, the following section discusses key findings that emerged from the narrative synthesis of the development process itself, positioning the findings as discussed in Oliveira et al. (2022) within extant literature. Additionally, the section presents the findings from an initial review and analysis of the final classifications and job placement of the first cohort to complete the programme. The student outcomes are presented to begin to evaluate the strengths and weaknesses of the structure described in detail by Oliveira et al. (2022) and to inform the future refinement and development of the course, and of architecture and engineering education more broadly. In this way, evidence will be added to support one of the indicators of engineering education success as described in Graham (2018), that is, the 'value added' to the student. This work also aims to help fill the gaps defined by Richter and Paretti (2009), notably a lack of measurable outcomes of interdisciplinary engineering education.

Findings

Narrative analysis

A key ingredient to developing multidisciplinary curricula was found to be ensuring that the team has a shared ethos and understanding, flexibility and agility in meeting both professional and personal expectations of the process, and critically obtaining institutional support. These findings are echoed in much of the literature on multidisciplinary education and practice. Power and Handley (2019) discuss three interrelated approaches for better integration of interdisciplinarity in HE including, maintaining clear communication, providing an adequate structure, and facilitating cultural change through shared values.

In the Oliveira et al. (2022) study these shared values were found by the participants to be not only of a professional character but also deeply personal. Some participants observed and discussed the importance of conveying a sense of a 'common desire' to achieve an 'integrated approach' that 'realised the importance of each team'. In addition to shared beliefs, most participants reflected upon a sense of having 'a blank sheet of paper' when developing the course content to ensure that all content created was bespoke and could fit the diverse professional body criteria. This 'ground-up' approach differs from ways many similar interdisciplinary integrated courses develop by fitting around shared modules and content. Professional expectations were also found to reflect many of the participants own professional experiences, working across disciplines with many discussing the importance of that experience to provide the skills to transcend disciplinary boundaries. Whilst many described the future graduate to be a new type of professional, a 'building designer' as well as a 'specialist generalist', many also discussed the potential other possibilities the course could offer to a developing industry need for greater collaboration and integration.

When personal expectations were discussed, these tended to convey the practicalities of developing shared values such as maintaining a positive focus and ensuring starting points and goals were well communicated. Some describe the inherent challenges of communicating across differing disciplinary expectations and the need for maintaining a shared vision and positive outcomes as critical to managing those differences. For many, their life experiences beyond the course shaped their understanding of their particular roles in the course development – seen by some as fulfilling the role of negotiators, others as visionaries. Whilst much of the detail was uncertain at the start of the discussions, there was a wider acceptance that the process was largely unknown and flexibility and agility to adapt to the process was observed by all as key. The need for flexibility and agility supports and extends work by Clevenger et al. (2017) on the importance of a shared programmatic and course level vision as well as providing opportunities for iteration and risk taking in facilitating multidisciplinary curricula.

Whilst being mindful of both professional and personal expectations was found by all to matter, the critical, and possibly most significant challenge, was obtaining institutional support. The institutional support and resource to ensure all content created and developed was bespoke to the needs of the course was found to be a critical component of the discussions' successful outcome. Insights also suggest that willingness to take risks by both the institution and the course developers is critical to the success of the course development process. Participants discussed the process of developing the course as being challenging as well as open and a venture into the unknown. Many participants stressed the importance of the course being a new type of discipline- neither engineering nor architecture. Institutional support as well as having the possibility of the course being delivered in a purpose-built facility driven by a design studio style teaching delivery were important factors in maintaining vision as well as overcoming cross departmental challenges. Many participants discussed the importance of 'maintaining ambitious vision' as an important aspect of the course development conversations. The need for institutional support is also reflected in other studies as a key condition to enabling multidisciplinary curricula to evolve (Richter & Paretti, 2009).

Review of the outcomes of the first cohort

According to UCL's Bartlett School of Architecture (BSA), there are 300 permanent members of staff at BSA and 1,600 undergraduate and postgraduate students, or an academic staff to student ratio of approximately 1:5. In comparison the academic staff to student ratio for UCL as an institution is approximately 1:10. The MEng Engineering and Architectural Design has about 30 primary teaching staff and 44 tutors for a maximum 'steady-state' student enrolment of 240 (60 per year for 4 years), or a staff to student ratio of just over 1:3, making this a staff-resource intensive programme.

Thirty students made up the first cohort, and as of May 2021 twenty-three had completed their dissertation. The average final dissertation mark was 71, the highest mark was 88 and the lowest mark was a 44; where marks above 70 are equivalent to an 'A', 60-69 a 'B', 50-59 a 'C', and marks below a 50 are fails. Results from eighteen students of this first cohort were reviewed, sixteen with a Master of Engineering and two with a Bachelor of Engineering. Of those who completed the MEng eight earned first class honours with final marks above 70; seven received second class honours (upper division) with marks above 60; and one earned a second class honours (lower division) with a mark above 50. In modules that are shared across programmes, the students enrolled in the MEng EAD programme were some of the highest performers. Reasons for this could, in part, be due to the type of students that were attracted to the nascent programme. Information gathered from initial interviews with staff suggest that the first cohort were largely self-motivated high achievers. It is unknown if the distribution of final classifications will remain skewed to as many distinctions as the programme matures.

Early reports from graduates and employers indicate high rates of employment with some students receiving offers of employment as early as the first term of their final year. Comments from employers suggest that the broad set of skills learned by graduates is very desirable. However, both students and employers expressed concerns about how, or where, they fit into a traditional practice. Approximately one quarter of the first two graduating quarter are working towards RIBA Part 1, another 25% report employment as 'graduate structural engineer', an additional quarter list their job as 'architectural engineer' or as part of a sustainability team, the remaining graduates report a wide variety of job types including, digital media, robotics, or further education (e.g., RIBA Part 2).

Further evaluation of the programme through extensive interviews with graduates, current employers, and staff is on-going.

Conclusion

It is well established that developing multi-, inter-, and transdisciplinary curricula is a complex endeavour and that it requires coordinated efforts by academics and industry from different university departments and different disciplines. However, it is less well known that coordination and communication of such efforts can also be shaped by professional and personal expectations as well as institutional contexts as discussed above. In addition, many of the academics involved in the course development discussed above had prior experiences of working or learning in multidisciplinary environments and this prior experience and knowledge enabled an open mindset and positive focus on shared outcomes.

Whilst the implications of this study are primarily in advancing engineering and architecture curricula, there are helpful insights that might benefit other curricula in other engineering disciplines. For instance, the importance placed on personal experiences and expectations. Most participants engaged in developing this course had some prior experience of multidisciplinary curricula, either as students or educators in past institutions. There may be further helpful benefit in developing STEM professional courses or seminars that could offer insight and experience of learning in a multidisciplinary environment, leading to a positively led curricular approach that merges and draws on different disciplines. Whilst the participants did not reflect on the role of the environment both on terms of equipment or space needs, it may have been helpful to further explore how the physical design of a very novel and bespoke space facilitated or enabled certain curricular understandings or discussions. Future studies could further explore how this novel environment may inform or enable particular types of activities and learning environment that otherwise may not have been possible. It is also recognised that this study is based on one course. Future studies could compare course development processes with regards to multidisciplinary content of two or more courses, perhaps across different sectors or between different countries. Future studies are also needed to analyse further the role different people and their activities, vision and expectations play in developing multidisciplinary content.

Transcending multiple disciplinary boundaries is becoming increasingly important for devising solutions to the world's most pressing issues, such as climate change and decarbonisation. Multidisciplinary education offers opportunities to help develop new competencies and attributes of future built environment professionals. There is emerging evidence, from the review of the interdisciplinary MEng programme in Engineering and Architectural Design at UCL, that both students and industry find the educational approach to be of great value. The insights from this paper offer helpful pathways to how curricula that ensure development of new competencies could be considered.

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SUPPORTING THE CASE FOR BSC/|MENG SUSTAINABLE BUILT ENVIRONMENTS, ENERGY AND RESOURCES

Tim Dwyer

Introduction

This is a collection of materials abstracted from recent communications published by influential, and informed, advocates on the necessity to deliver a sustainable built environment that economically utilises energy and resources with minimal impact on the current and future global environments. The knowledge, skills, attributes and qualities that are explored and articulated can be directly mapped to curriculum areas within the proposed programme or are conceptually seeded through context based studies. Graduates from the course will develop knowledge and expertise to become leading practitioners able to evolve and innovate policy and design, and so create and deliver, sustainable built environments as expounded in these publications.

In his foreword to the 'Sustainable living places – a systems perspective on planning, housing and infrastructure'[1] Alan Penn, Chief Scientific Adviser to Ministry of Housing Communities and Local Government, notes that "the issues that surround sustainability and those that involve the local contexts of place figure among the most complex and urgent that currently face us. The challenge of delivering net zero carbon by 2050 is possibly the largest in human history to date. It is also the most urgent. It is estimated that buildings account for up to 40% of greenhouse gas emissions." As the second, of six 'enablers and inhibitors' the report identifies the crucial role of education in creating holistic living places and the need for integration between universities and the sustainable living place.

In the joint resiliency statement[2] the two leading international institutions focussing on the engineered internal environment, ASHRAE and CIBSE, shared their mutual positions that built environments need to be developed which are both resilient and sustainable and that resiliency is an increasingly important societal, economic, and technical issue that will have a major impact on how built environments in general, and engineered systems in buildings, are designed and operated.

The UK Engineering Council[3] lists six principles to guide and motivate engineers when making decisions for clients, employers and society which affect sustainability:

- Contribute to building a sustainable society, present and future
- Apply professional and responsible judgement and take a leadership role
- Do more than just comply with legislation and codes
- Use resources efficiently and effectively
- Seek multiple views to solve sustainability challenges
- Manage risk to minimise adverse impact to people or the environment

The Royal Academy of Engineering has set five foundations for a net-zero-recovery (following Covid-19).[4] The final two of these highlight the need to drive digital transformation as an essential enabler of net-zero and resilience through improvements to existing infrastructure and buildings. They also identify the importance of cross-sectoral systems approaches to policymaking that underline the interconnectedness of different policy areas and economic sectors. This will ensure that policy interventions work most effectively together to achieve net-zero and deliver co-benefits, reduce the risk of 106 unintended consequences, and help account for social, cultural and behavioural factors, which can act as both barriers to and levers for change.

In a paper[5] by Sachs ("Probably the most important economist in the world- New York Times) he provides routes to achieving the 17 UN Sustainable Development Goals (SDGs) that underpin the 2030 Agenda for Sustainable Development.[6] These include improved energy efficiency in final energy use, including heating and cooling of buildings and the electrification of current uses of fossil fuels such boilers and heaters. He emphasises that circularity and decoupling without lowering human well-being must underlie all SDG transformations.

In the regular biennial market study of sustainable buildings[7] undertaken by Ramboll (a 16,000 strong global engineering, architecture and consultancy company) the key future trends reflected by respondents in 2019 included that they expect 57% or more of their future projects to be sustainable -significantly up from 50%

in 2017. The top 5 'essential' future trends were health and wellbeing; resilience against climate change; life cycle thinking and management; and carbon neutrality. Digitalisation is anticipated as the potential key to providing a pathway to facilitate these future trends.

A similar message of growth was provided by the survey for World Green Building Trends 2018 that indicated an increasing percentage of respondents who expect to do the majority of their projects (more than 60%) 'green' in most of the 20 countries/regions that they represent. The percentage who expect they will be doing the majority of their projects green by 2021 is expected to double clearly demonstrating increasing global commitments to building green. They also reported a steady growth since 2012 in the number of owners who see a 10% or greater increase in asset value for new green buildings compared with traditional ones.[8] World Bank estimates that a transition to low-carbon and resilient economies could create tens of millions of new jobs and trillions of dollars of economic growth.[9]

Municipalities and governments around the world are issuing 'sustainability' and 'resiliency' policies in efforts to raise awareness of the increasingly desperate need for action. This, naturally, includes most of the major international cities but also includes less high profile, but equally earnest locales. As reflected by the review of policies to promote sustainable development in London, the impact of COVID-19 is likely to cause a major recession and significant unemployment, whilst exacerbating existing inequalities. Meanwhile, climate and ecological emergencies have not gone away, and the policy and investment decisions we make now must lock in a zero-carbon, circular economy. But a green and fair recovery is not just the right thing to do: it is the most economically advantageous approach. The town council of Milton Keynes recent published a draft sustainable construction policy[10] that aims to ensure new development is responsible for as little carbon emissions as possible to meet a net zero carbon target, as part of a national and global effort to prevent the worst impacts of climate change. This considers broad categories within development activity and the built environment which relate to sustainability including:

- Performance certification (BREEAM) for Non-Residential Buildings
- Materials and waste
- Energy and climate
- Water
- Retrofitting (refurbishment)

Retrofits also have a large 'economic multiplier' effect: every percentage point of GDP invested in this way is expected to increase UK GDP by 2 - 3%.[11]

Korn Ferry (ranked by Forbes[12] as the "#1 executive recruiting firm" and "#2 professional recruiting firm" in the U.S in 2019) recently wrote[13] on the important role of Chief Sustainability Officers (CSOs) and their teams with responsibilities that focus on resilience as a core part of business strategy and embedding positive social impact within the organisation's purpose. It resolved that sustainability is more than an individual or function, it is a strategy with purpose. Its mandate is to make the business take ownership of the agenda, shift operating models and ways of working, and can ultimately provide a competitive advantage in the market through product or service innovation, improved trust, cost reduction and resilience.[13]

In his recent essay Winston[14] ("The go-to-guru on all things green"[15]) reflected that… "what's clear is that we're in the middle of a major re-alignment of values around climate. It's now unacceptable to young activists, and the millions of people they inspire, to espouse climate denial or play the "let's go slow" card. They don't appreciate being handed a disaster movie for them to live with for 70 to 80 years."

Leading nanotechnology pioneer and technology commentator Seeram Ramakrishna recently wrote[9] that one prevailing view is that sustainability is not the core business of universities, and it is the agenda of governments, businesses and the consumers and that the multitude of sustainability articulations thus far are often perceived as broad vision statements and goals, and not with sufficient details to build or reposition the respective curriculum of academic programs, departments, schools/faculties/colleges, and universities. There is also general inertia for making changes ahead of time due to the misheld perception that there will not be enough career opportunities for all the sustainability focused graduates. He asserts that academic leaders need to focus on designing and developing new and creative sustainability education programs fundamentally and radically different from the current established practices. This requires deeper and stronger collaboration among the faculty members of diverse disciplines and expertise.

As presented on UCL's web pages[16] "Education for sustainable development is the process of equipping students with the knowledge and understanding, skills and attributes needed to work and live in a way that safeguards environmental, social and economic wellbeing, both in the present and for future generations. A 'glocal' curriculum (a term popularised[17] by influential philosopher and scientist Guido Caniglia) conceives of sustainable development in terms of problems and solutions in local and global contexts" … and … "empowers students to contribute to social change across cultural and geographical contexts. Therefore education for sustainable development lends itself to real-world case studies, project-based learning and the use of the campus as a learning resource".[16]

In the recent paper by Caniglia[18] et al. it is promoted "that efforts to create change should be based on pluralistic and integrated learning processes of knowledge co-production, action and capacity building and that if applied to the knowledge that informs action and capacity building for sustainability, integrative pluralism, first, allows for recognizing that action-oriented knowledge for sustainability relies on a plurality of kinds of knowledge and ways of knowing. It encourages actors involved in such processes to work in integrated ways… in situations characterized by normative uncertainty, political contestation and conflict. Although this does not mean reaching agreement or consensus across conflicting views and interests it means engaging with conflict and contestation collaboratively when navigating the emergent dynamics of intricate action and capacity building processes. Integrative pluralism combined with pragmatism implies that one may never reach an end-goal of enough knowledge when tackling complex phenomena, because the kinds of knowledge and ways of knowing involved are always being developed through action and interactions in complex and recursive learning processes. The variety of teaching and learning methods in this predominantly project based and enquiry-based programme will develop and reinforce these lifelong pluralistic and integrated learning processes.

The pedagogy of this programme will also be designed to develop competences that, as exemplified by[19] by Senge (internationally recognised management expert and author 'The Fifth Discipline: The art and practice of the learning'), ensure graduates are equipped to develop three core capabilities required by leaders in order to foster collective leadership. The first is the ability to see the larger system that is essential to building a shared understanding of complex problems. The second involves fostering reflection and more generative conversations enabling groups of organizations and individuals to actually "hear" a point of view different from their own, and to appreciate emotionally as well as cognitively each other's reality. The third capability centres on shifting the collective focus from reactive problem solving to co-creating the future…..as leaders help people articulate their deeper aspirations and build confidence based on tangible accomplishments achieved together.

The WorldGBC Annual Report 2020[20] identifies that 11 of the 17 United Nations SDGs are directly impacted by the built environment and, amongst other key actions, advocates a total decarbonisation of the built environment. This promises a built environment that delivers healthy, equitable and resilient buildings, communities and cities; and supports the regeneration of resources and natural systems, providing socioeconomic benefit through a thriving circular economy. The future, as expounded in this collection of abstracted documents, will require academics, researchers, practitioners and leaders who would significantly benefit from, and be set on a path to, a worthy and worthwhile lifelong vocation having successfully studied and graduated from this proposed programme.

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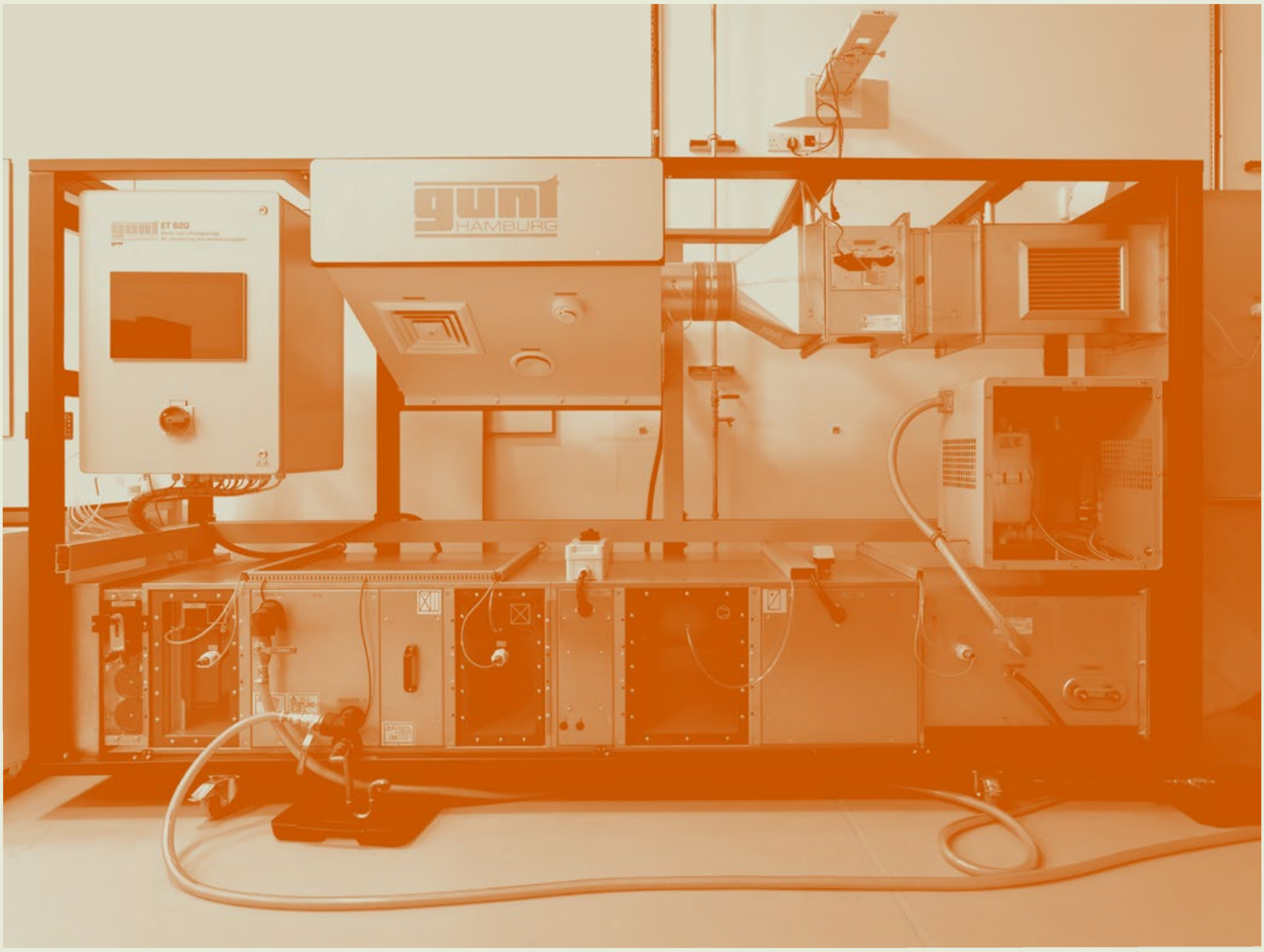
Students from Sustainable Built Environments, Energy
and Resources (SBEER) Programme at Sustainability Centre
2024/2025 (image credit: Nahid Mohajeri)

COLLABORATION WITH INDUSTRY

INDUSTRY CO-FUNDED RESEARCH AND FACILITIES

INDUSTRY CO-FUNDED RESEARCH AND FACILITIES

Contributors: Esfandiar Burman, Edward Barrett, Rokia Raslan



Components of a mechanical ventilation system (HVAC Lab)
(Image credit: IEDE staff)

1. Introduction

Innovation and Enterprise are an integral part of a changing academic landscape for UK universities. At The Bartlett, engagement, collaboration and innovation with enterprises, policy makers and local communities are a key aspect of the work we do and a cornerstone of our research impact and teaching activities. This focus recognises our core strengths in research and teaching while creating mechanisms to further the reach of our successes in these areas. Our practical and forward-looking strategy in this area aims to:

– Use our knowledge and intellectual assets to address major societal and economic challenges
– Work with innovative partners across the public and private sectors to address collaborative opportunities that amplify our innovation activity
– Promote and embed an effective culture of innovation and knowledge exchange

The UCL Institute for Environmental Design and Engineering (IEDE) has a long track record of translating world-leading research into powerful competitive advantages for partners in industry, government and charity. We also envisage a key role for innovation in strengthening the IEDE's presence and role as a global leader in our field. We work with companies of all sizes, as well as government departments and agencies, NGOs and small, focused charities. We tailor each partnership to fit precise needs, whether in the form of a research and development partnership, a Knowledge Transfer Partnership (KTP), consultancy or continuing professional development training. Below are some examples of different partnership relationships we have engaged in over the past few years.

2. Research Collaborations with Industry

These collaborative projects, facilitated by funding from research councils, are supported by our partners from the construction industry, consultancies, central government, charities and professional institutions. They co-fund our research, support our students' work and provide a route to impact and future employment.

The UCL Centre for Virtual Environments, Interaction and Visualisation (VEIV) was founded following a successful bid in response to an Engineering and Physical Sciences Research Council (EPSRC) call for new Engineering Doctorate (EngD) centres. VEIV focused on projects that advance the science and engineering of computational capture, rendering and simulation in a diverse range of applications. VEIV ran a Master of Research (MRes), an EngD and a PhD programme, through which research engineers were fully co-funded to undertake research relating to virtual environments, imaging and visualisation in engineering and design. Table 1 lists the details of the IEDE doctoral projects and industry collaborations facilitated by VEIV.

Table 1. IEDE collaborative projects, VEIV, 2010–2018

Research topic	Collaboration	Doctoral researcher	UCL supervisors
Occupant satisfaction in non-domestic buildings	BSRIA	Roderic Bunn	Ljiljana Marjanovic-Halburd, Paul Ruyssevelt
Communication technologies to deliver public health agendas in NHS food and drink automated vending	Barts Health NHS Trust	Lucy Zarina Fraser (Campbell)	Michael Pitt, Peter McLennan
Decision-based and BIM-embedded optimisation framework for reinforced concrete building structures	Price & Myers	Stathis Eleftheriadis	Dejan Mumovic, Philippe Duffour
An integrated decision support framework for the refurbishment or replacement of buildings	Hawkins\Brown	Yair Schwartz	Dejan Mumovic, Rokia Raslan
Quantifying and mitigating differences between predicted and measured energy use in buildings	Buro Happold	Chris van Dronkelaar	Dejan Mumovic, Catalina Spataru
A probabilistic approach for the moisture risk assessment of internally insulated solid walls	Natural Building Technologies	Valentina Marincioni	Hector Altamirano-Medina, Mike Davies
Physical asset lifecycle modelling in the healthcare sector	Modus	Amir Nabil	Michael Pitt, Peter McLennan
Condition-based maintenance: innovation in buildings maintenance management	Skanska	Ruhul Amin	Michael Pitt, Peter McLennan
Terahertz time-domain spectroscopy and imaging of archival documents	TeraView	Tiphaine Bardon	Matija Strlic, Michael Pepper
An imaging tool for energy-efficient communities of the future	BRE	Ciro Bevilacqua	Ben Croxford, Dejan Mumovic
Lifecycle carbon impact of higher education building redevelopment	Feilden Clegg Bradley Studios	David Hawkins	Dejan Mumovic, Alex Summerfield
Real-time energy-use predictions at the early architectural design stages	Aedas	Grieg Paterson	Dejan Mumovic, Payel Das
A sociotechnical method to assess the holistic impact of new buildings on English secondary schools	Feilden Clegg Bradley Studios	Joe Williams	Dejan Mumovic, Kerstin Sailer

The London–Loughborough EPSRC Centre for Doctoral Training in Energy Demand (LoLo CDT) was set up to address new challenges within five themes: technology and systems, energy epidemiology, urban-scale energy demand, building performance and process, and unintended consequences. Table 2 lists the details of the IEDE doctoral projects and industry collaborations facilitated by the LoLo CDT.

Table 2. IEDE collaborative projects, LoLo CDT, 2016–2022

Research topic	Collaboration	Doctoral researcher	UCL supervisors
Developing a crowdsourcing sociotechnical school building stock model	VEIV	Duncan Grassie	Dejan Mumovic, Ivan Korolija/Yair Schwartz
Quantifying the benefits of measures to reduce the exposure of deprived communities to air pollution	Public Health England (PHE)	Lauren Ferguson	Mike Davies, Phil Symmonds
Development of a Bayesian calibration framework for building stock models of summer indoor temperature	CIBSE	Giorgos Petrou	Anna Mavrogianni, Phil Symmonds
Thermal comfort and air quality control in UK student accommodation	Bouygues	Anthony Marsh	Paul Ruyssevelt, Ivan Korolija
The relationship between ventilation practices, indoor air quality, noise and overheating in UK homes	Public Health England (PHE)	Cairan Van Rooyen	Cliff Elwell, Mike Davies

The London–Loughborough EPSRC Centre for Doctoral Training in Energy Demand (LoLo CDT) was set up to address new challenges within five themes: technology and systems, energy epidemiology, urban-scale energy demand, building performance and process, and unintended consequences. Table 2 lists the details of the IEDE doctoral projects and industry collaborations facilitated by the LoLo CDT.

Table 3. IEDE collaborative projects, SEAHA CDT, 2017–2023

Research topic	Collaboration	Doctoral researcher	UCL supervisors
Total performance of UK Passivhaus primary schools	Architype	Chryssa Thoua	Anna Mavrogianni, Dejan Mumovic
Evaluating energy and indoor air quality potential impact of spray foam: a case study of robotic application	Q-Bot	Dzhordzhio Naldzhiev	Dejan Mumovic, Matija Strlic

Energy Resilience and the Built Environment EPSRC and Science Foundation Ireland Centre for Doctoral Training (ERBE CDT) trains future energy and built environment leaders and innovators. Students are trained through a programme of taught courses and PhD research hosted by the leading energy research groups in the UK and Ireland. The training is led by world leaders in their field and spans the technical, social and economic aspects of energy in the built environment, including: new and renewable energy systems; energy storage; smart controls; data analytics; sociotechnical systems; people-centred design; human behaviour and energy economics. Table 4 lists the details of the ongoing IEDE doctoral projects and industry collaborations facilitated by the ERBE CDT.

Table 4. IEDE ongoing collaborative projects, ERBE CDT

Research topic	Collaboration	Doctoral researcher	UCL supervisors
Scalable method to assess ventilation rates in dwelling	Aereco	Jalal Ahmed	Hector Altamirano-Medina, Dimitrios Rovas
Smart and healthy higher education buildings and campuses	Feilden Clegg Bradley Studios	Eleni Davidson	Dejan Mumovic, Yair Schwartz
Climate-responsive building design	Feilden Clegg Bradley Studios	Simon Vakeva-Baird	Dejan Mumovic, Farhang Tahmasebi
Investigating the performance of solid walls with water-repellent surface treatments	SPAB/Safeguard	Toby Cambray	Hector Altamirano-Medina, Valentina Marincioni
Dynamic holistic LCA: integrating embodied and operational carbon, energy, water and wider ecosystem impacts	Buro Happold	Marios Kordilas	Dejan Mumovic,Yair Schwartz
Smart buildings design and digital engineering	AHMM	Meysam Paydar	Esfandiar Burman, Dejan Mumovic
Empirical assessment of health and wellbeing in low-energy buildings	Architype	Bhargav Macha	Anna Mavrogianni, Rokia Raslan
Urban climate and energy system resilience and adaptability	Hoare Lea	Yingyue Li	Esfandiar Burman, Rui Tang
Exploring pathways for decarbonising and improving resilience of NHS healthcare facilities in England	Energy Systems Catapult/NHS/CIBSE	Yingyan Li	Sung-Min Hong, Rui Tang
Decarbonisation and energy resilience of the museum sector	V&A (in-kind contribution)	India Golding	Scott Orr, Sung-Min Hong

Another model of fostering industrial collaboration is the Doctoral Training Partnerships created by Collaborative Awards in Science and Engineering (DTP CASE), supported by the EPSRC. Table 5 lists the details of the IEDE doctoral projects and industry collaborations facilitated by these partnerships.

Table 5. IEDE collaborative projects, DTP CASE

Research topic	Collaboration	Doctoral researcher	UCL supervisors
Timeless digital twins for the energy–health nexus	Atelier Ten	Alex Fung	Dejan Mumovic, Ivan Korolija
Rethinking energy retrofit for social housing through user perspective: making homes comfortable, healthier, energy-efficient	Historic England	Athina Petsou	Hector Altamirano-Medina, Sung-Min Hong
Agile architecture: how the built environment can learn from how it is used	Steensen Varming	Simone Bonavia	Jemima Unwin, Peter Raynham
Hotel lobbies as workplaces for the modern worker	KSBC	Dolapo Oluteye	Peter McLennan, Ben Croxford
Integrated multi-vector smart energy systems at building, campus and neighbourhood scales	Buro Happold	Vasiliki Kourgiozou	Dejan Mumovic, Dimitrios Rovas

Table 6 lists the details of the other collaborative doctoral projects at IEDE.

Table 6. Other IEDE-funded projects

Research topic	Collaboration	Doctoral researcher	UCL supervisors
Active reduction of noise transmitted to and from enclosures	MSCN studentship	Zulfi Rachman	Jian Kang, Francesco Alett
Smart buildings at scale: a semantic framework for data reusability and application portability	H2020 project	Dimitris Mavrokapnidis	Dimitrios Rovas, Ivan Korolija
Productivity and wellbeing in the 21st-century workspace: implications of choice	Cushman & Wakefield LLP	Madalina Hanc	Alexi Marmot, Anna Mavrogianni
Lighting design with LEDs	Electron SA	Panagiota Hatziefstratiou	Peter Raynham, Kevin Mansfield
Towards advanced analytic strategies for estimating air temperature through remote sensing	National Council for Scientific and Technological Development (CNPq), Brazil	Rochelle Santos	Mike Davies, Jonathon Taylor
Dynamics of place-based decision-making: a systems approach to leverage social housing regeneration for health and sustainability	National Institute for Health and Care Research	Ke Zhou	Nici Zimmermann, Marcella Ucci

3. Knowledge Transfer Partnerships

KTPs help drive innovation and growth by creating collaborations between businesses and academic institutions. KTPs are tailored to the specific requirements of individual partnerships, each addressing specific needs. Through the placement of highly qualified KTP associates (typically PhD holders or other graduates with significant relevant experience), businesses gain innovative solutions, new technologies and expertise over 12–36 months. IEDE has been very successful in creating new partnerships with industry, supported by Innovate UK. Table 7 provides details of the partnerships created following this model of supporting innovation and enterprise.

Table 7. IEDE Knowledge Transfer Partnerships

KTP project topic	Partnership	KTP Associate	Academic Team
AI for innovative and sustainable retrofit design	ECD Architects	Robin Roussel	Esfandiar Burman, Rui Tang
Energy efficiency and moisture risk assessment	Q-Bot	Apostolos Evangelopoulos	Hector Altamirano-Medina, Valentina Marincioni
Achieving net zero carbon in high-density mixed-use commercial developments	AHMM	Simon Hatherley	Dejan Mumovic, Esfandiar Burman
The impact of innovation in facilities management (FM) service delivery	Amey	Anna Walker	Michael Pitt, Peter McLennan
Closing the performance gap using calibrated building simulation models	DesignBuilder	Nishesh Jain	Dejan Mumovic, Esfandiar Burman
Designing sustainable buildings across the world using hybrid-cloud computing	FCBStudios	Daniel Zepeda Rivas	Dejan Mumovic, Farhang Tahmasebi
Evaluating commercial buildings' technological service characteristics to meet industry standards	KSBC	Amer Alwarea	Peter McLennan, Ben Croxford
Excess moisture in the built environment	Property Care Association (PCA)	Paula Lopez-Arce	Hector Altamirano-Medina, Dimitrios Rovas
Decarbonising technologies	Tesco	Wenzhuo Li	Dejan Mumovic, Ivan Korolija Rui Tang
Low-energy ventilation systems	Ventive	Paraskevi Vivian Dorizas	Dejan Mumovic, Samuel Stamp

4. A Living Lab Ecosystem for Research and Innovation

Our high-tech facilities and laboratories provide an opportunity to undertake groundbreaking research and are also an integral part of our teaching.

IEDE's **high-performance environmental chambers** include a **human chamber** that provides precise control of temperature, humidity, ventilation rates, and carbon dioxide levels for studies into occupant comfort and cognitive performance. **Thermal chambers** also provide control over temperature, humidity and ventilation rates, with the capacity to simulate driving rain. This allows high-level testing of building materials and components, supporting the work of the UK Centre for Moisture in Buildings.

A gas chromatograph/mass spectrometer system can also be used to investigate emissions from materials and analyse volatile organic compounds.

The variable-luminance **Artificial Sky** is a custom-designed 5.2m-diameter hemispherical dome that contains 810 individually addressable energy-efficient LED modules. This is used to simulate different daylight distributions. There is also a parabolic reflector that is positioned automatically in the dome to follow the path of the sun for a given day. Students can use this tool to explore the daylight performance of new buildings, as well as how to take advantage of daylight in buildings. Our light and lighting facilities also include a darkroom that is used for a wide range of optical and vision experiments, in research as well as teaching. Figure 2 shows the Artificial Sky colour test. The colour of the LED modules cannot be directly controlled. However, they can be made to create an arbitrary distribution of light. Here different distributions have been used for each of the red, green and blue channels of the image. This creates the impression that the room was lit with coloured lights.

Figure 1. The human chamber used for a performance task in a controlled environment (left), and a material chamber (right) (Image credit: IEDE staff)

The **Audio Lab** provides the ability to work with immersive audio. It uses an array of speakers to reproduce spatially accurate sonic environments. A virtual reality headset with integrated eye tracking is also available for increased ecological validity. The Audio Lab supports the work of the 'Soundscape Indices' project instigated by a European Research Council (ERC) Advanced Grant, and PhD and MSc student projects at the IEDE Acoustics Group.

A state-of-the-art **HVAC Lab** offers a space for practical sessions and demonstrations for up to 60 students. The lab includes an educational air handling unit to demonstrate components of mechanical ventilation systems, a modular heat pump, different heating terminals, a solar thermal system, heat storage cylinders and the use of building controls. It also allows for the simultaneous streaming of live energy and environmental performance data to the lab from current research projects.

To facilitate world-leading research in the built environment, we also have over one thousand individual items of field equipment for off-site use by our researchers and students involved in building performance evaluations. These include high-resolution thermal cameras, spectrometers, particle detectors, blower door kits, smoke guns, and an array of sensors and data-logging systems to evaluate energy performance, occupant behaviour (e.g. occupancy, window opening), ventilation system performance, indoor air quality, thermal comfort, moisture and humidity, acoustics and lighting performance.

Equipment is available for teaching demonstrations, practical assessments and dissertation projects, and for students to loan out and use independently. All research equipment may be used for these purposes, with a dedicated range available for students to take on site or field trips.

Figure 2. Artificial Sky colour test (Image credit: IEDE staff)

Figure 3. The Audio Lab (Image credit: HHB)

Figure 4. The modular heat pump system (HVAC Lab) (Image credit: IEDE staff)

Acknowledgements

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ALLFORD HALL MONAGHAN MORRIS

ARCHITYPE
atelier ten
NHS Barts Health NHS Trust
BOUYGUES

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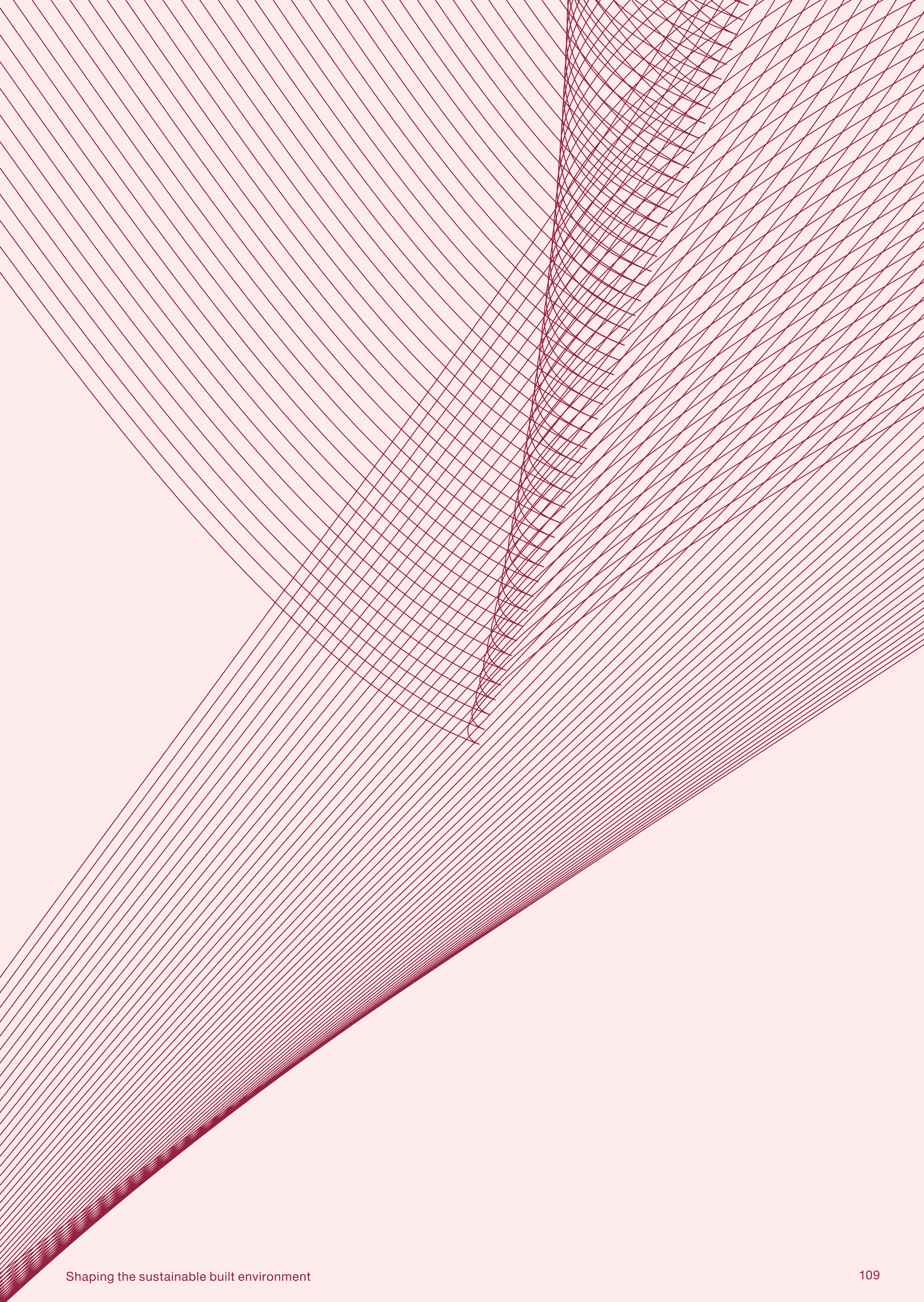
BURO HAPPOLD
CATAPULT Energy Systems

CIBSE
CUSHMAN & WAKEFIELD
CNPq Conselho Nacional de Desenvolvimento Científico e Tecnológico
DesignBuilder

ECD Architects ENERGY CONSCIOUS DESIGN
ELECTRON
Feilden Clegg Bradley Studios
Hawkins\Brown

RESEARCH



RESEARCH THEMES OVERVIEW

Marcella Ucci and Nici Zimmermann

Introduction

The research vision at the UCL Institute for Environmental Design and Engineering (IEDE) is to deliver inter- and transdisciplinary built environment research to improve health, wellbeing and sustainability. In order to facilitate collaboration and foster the research culture at IEDE, staff and doctoral researchers collaboratively identified eight Research Themes. In this book, each Theme presents, in its dedicated chapter, a showcase of past and current research activities, and reflects on research challenges and opportunities, setting the research agenda for the future.

Our efforts to write this book to mark the 60th anniversary of Environmental Design and Engineering research at The Bartlett, UCL, were fuelled by a deep interest in inter- and transdisciplinarity and the idea of bringing our systems approach to the book's work. We thus worked on the chapters for each Theme in a participatory way, inviting colleagues and PhD students, as well as an exciting group of external scholars and practitioners, to enter a conversation on our research strengths, challenges and future agendas. Each Theme also worked on a diagram that represents one or several of the Theme's research challenges in greater depth. These diagrams show important interlinkages between the factors we work on and what we hope to achieve through this research. The aim was not to produce the best diagrams but to have at hand "boundary objects" (Black 2013; Star & Griesemer 1989) – that is, tools that stimulate discussion, that engage us in debate and help us manoeuvre the complexity of the challenges we address in our research by putting them visually in front of us.

In this chapter, we discuss cross-cutting aspects related to research at UCL IEDE and provide background information on the methods used to develop each Theme's chapter, particularly the causal loop diagrams (CLDs) mentioned earlier. Specifically, the next section outlines the process we followed to derive these diagrams. After that, we present a high-level diagram that integrates across our eight Research Themes, highlighting important interlinkages and opportunities for interdisciplinary research. The high-level diagram section is followed by a discussion of the highlights of the Research Theme chapters.

Methods: Diagram Development and Expert Workshops

We started from the idea of presenting a diagram of one or several important research challenges in each Theme. These diagrams are word-and-arrow maps. They very loosely follow guidelines for CLDs from the system dynamics modelling field, showing the causal structure between the factors we are interested in as researchers (e.g. Sterman 2000). Some of these factors reveal feedback loops – that is, circular chains of how our research and the outer world interact.

To arrive here, each Theme engaged in a co-creative process to develop a draft CLD. Some Themes held workshops among the Theme members. In other Themes, a smaller group of Theme members developed a draft diagram with the help of a system dynamics specialist. Each Theme then engaged a group of leading external scholars and, in some cases, practitioners in a workshop.

The aims of the workshops were to:
— validate the diagrams – that is, revise and improve them where necessary, and
— discuss future research pathways.

Either directly during the workshop or afterwards, we mapped these research pathways onto the diagrams to visualise our understanding of how our planned research activities would create real-world impact.

We continued our process of integration, looking for similarities and interdependencies between the eight CLDs, and developed an example of an integrated and overarching high-level diagram from this.

How to read the causal loop diagrams

The resulting diagrams show focus areas and outcomes as variables, as well as causal relationships between these. These relationships can have a positive or negative arrow polarity and they can form reinforcing or balancing feedback loops.

A positive arrow polarity indicates that when the cause increases (decreases), the effect will also increase (decrease), compared with what it would have otherwise been. A negative arrow polarity indicates that when the cause increases (decreases), the effect will decrease (increase), compared with what it would have otherwise been.

A reinforcing feedback loop further enforces a change in the system.

A balancing feedback loop somewhat balances and counteracts a change in the system.

UCL IEDE Research Themes: Highlights

IEDE Themes: The current structure of IEDE Themes emerged from discussions which started approximately five years ago, about our expertise and research agenda. While research is the key focus of the Themes' activities, they are also relevant to aspects of our teaching, enterprise and external engagement – as highlighted by the relevant chapters in this book. We currently have eight Themes:

— Light and Lighting
— Acoustics and Soundscapes
— Moisture, Temperature and Air Quality
— Climate Change, Sustainability and Cities
— Smart Buildings and Digital Engineering
— Life Cycle Assessment and Circular Economy
— Energy Use, Retrofit and Net Zero Carbon
— Systems Thinking and Transdisciplinarity

The Themes are a vehicle to stimulate activities and discussion among staff and doctoral researchers, whereby collaboration across Themes is strongly encouraged.

Causal loop diagram of interactions among the Themes: There are numerous interactions between the Themes, and Figure 1 and Figure 2 illustrate some of those that we think are particularly noteworthy. A shared concept among many Themes, sustainable decision-making and policy implementation, appears on the left of Figure 1, influencing Theme-specific outcomes such as the adoption of smart building technology, the number of buildings overheating, indoor air moisture, indoor environmental quality, urban greening, lighting quality and soundscape quality. These can collectively help address UCL IEDE targets of enhancing psychological, physiological and social value alongside mental, physical and public health.

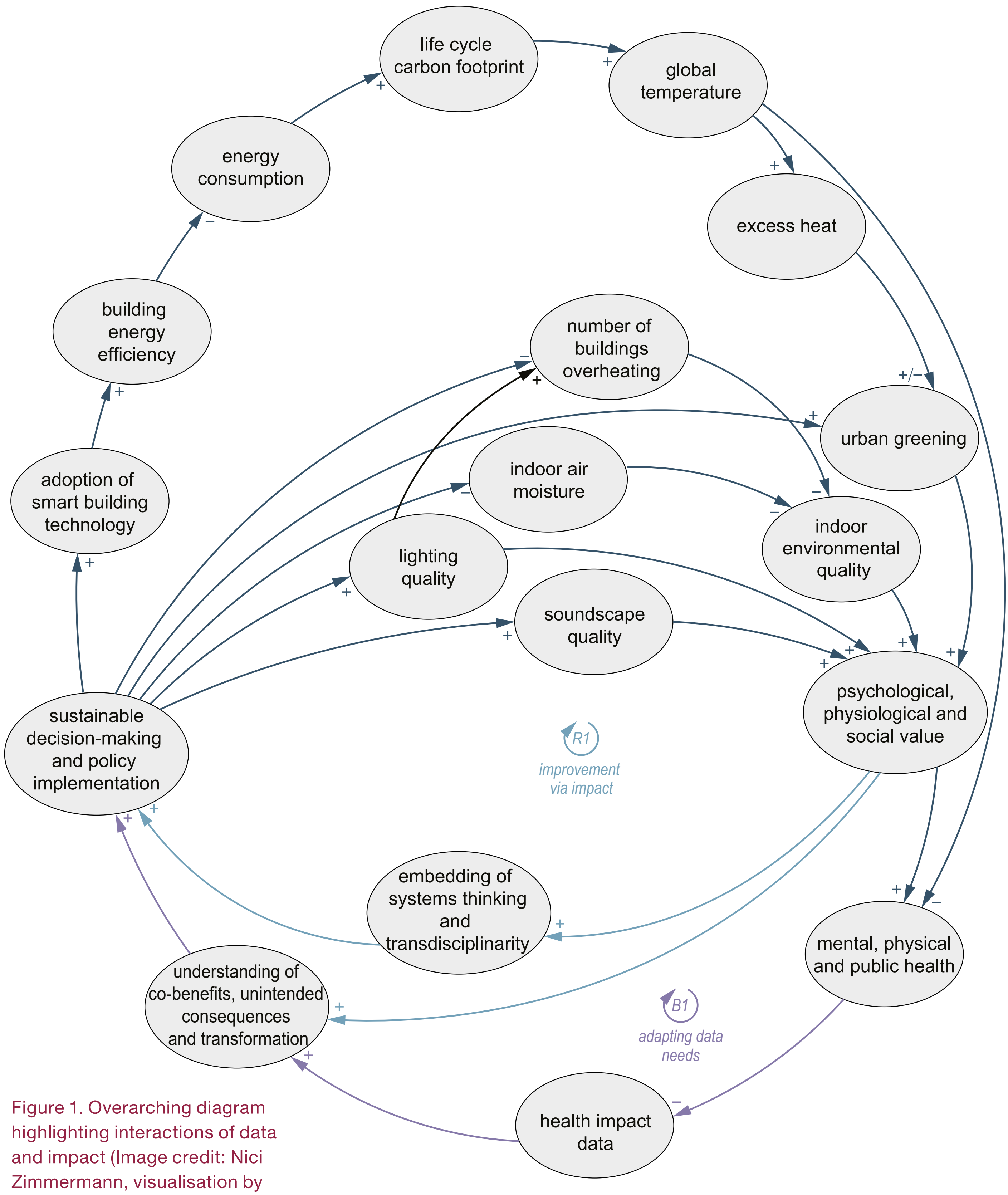
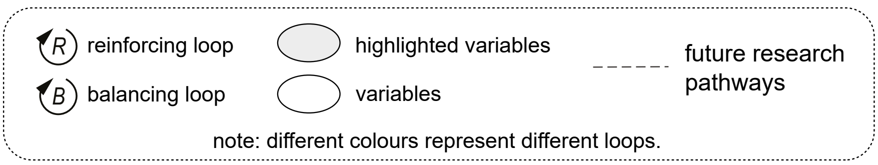


Figure 1. Overarching diagram highlighting interactions of data and impact (Image credit: Nici Zimmermann, visualisation by Daijia Ke)



Our research supports how value and health affect *sustainable decision-making and policy implementation* through two key mechanisms. First, via the reinforcing feedback loop 'R1: improvement via impact', recognising that value enhances the *understanding of co-benefits, unintended consequences and transformation,* supported by research evidence. It also helps *embedding systems thinking and transdisciplinarity*. These effects further support sustainable decision-making and policy implementation, creating a virtuous cycle that improves psychological, physiological and social value. Second, through the balancing loop 'B1: adapting data needs': poor mental, physical or public health can trigger demand for health impact data, which is how our research supports further evidence generation, improved understanding and implementation, as well as value and health.

The Smart Buildings and Digital Engineering and Light and Lighting Themes discuss how the adoption of smart building technology enhances building energy efficiency, which is a focus of many Themes. This reduces energy consumption and the buildings' lifecycle carbon footprint, a topic central to the Life Cycle Assessment and Circular Economy Theme, while also addressing global temperature and excess heat, key issues in the Climate Change, Sustainability and Cities Theme. This interconnected example demonstrates the substantial synergy between the work of various Themes.

The Theme diagrams reveal additional interactions, some of which are illustrated in Figure 2. Elevated energy consumption levels, represented in half of our Research Themes diagrams, along with a high lifecycle carbon footprint, motivate our research and real-world efforts on retrofitting and a transition towards net zero buildings. This transition enhances building energy efficiency and reduces energy consumption through the balancing feedback loop 'B2: adapting to net-zero'. This feedback mechanism serves as a critical structure in the system that, when nurtured by research and decision makers, can substantially advance progress towards achieving energy efficiency and carbon reduction targets.

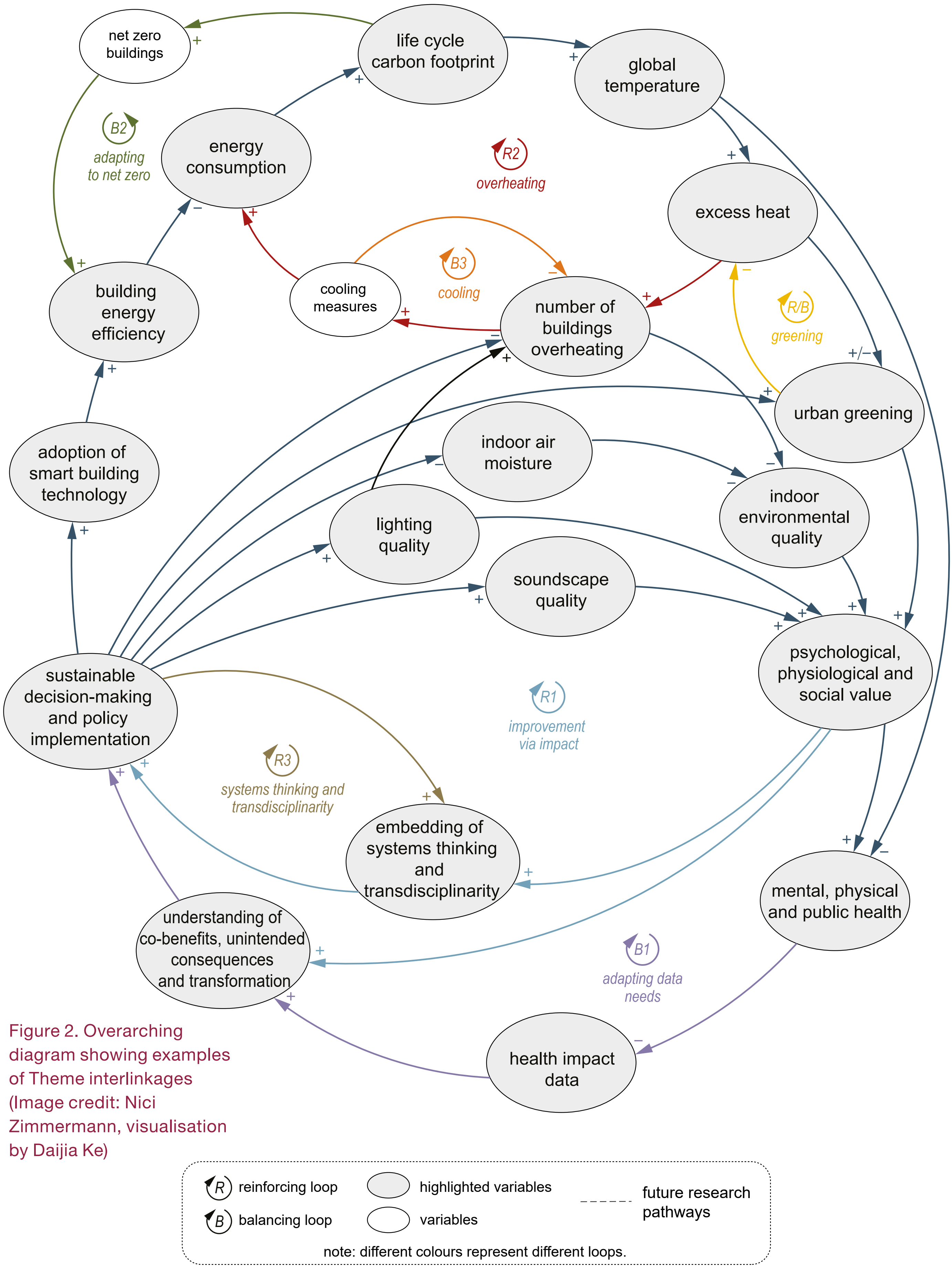


Figure 2. Overarching diagram showing examples of Theme interlinkages (Image credit: Nici Zimmermann, visualisation by Daijia Ke)

Interactions affecting global temperature and excess heat also influence the number of buildings overheating. This can prompt people to adopt cooling measures, which mitigate overheating, as depicted in the balancing feedback loop 'B3: cooling'. However, these measures increase energy consumption, closing the reinforcing feedback loop 'R2: overheating'. Our research also shows how this unintended consequence of active cooling can be mitigated by greater reliance on passive measures, as illustrated in the Energy USe, Retrofit and Net Zero Carbon Casual loop diagram (see page 224).

The Climate Change, Sustainability and Cities Theme highlights how excess heat has effects not only indoors but also in the natural environment, negatively affecting urban greening by preventing the growth of plants and creating a reinforcing vicious cycle. However, measures to actively increase urban greening with rising heat could add a balancing mechanism and eventually generate psychological, physiological and social value.

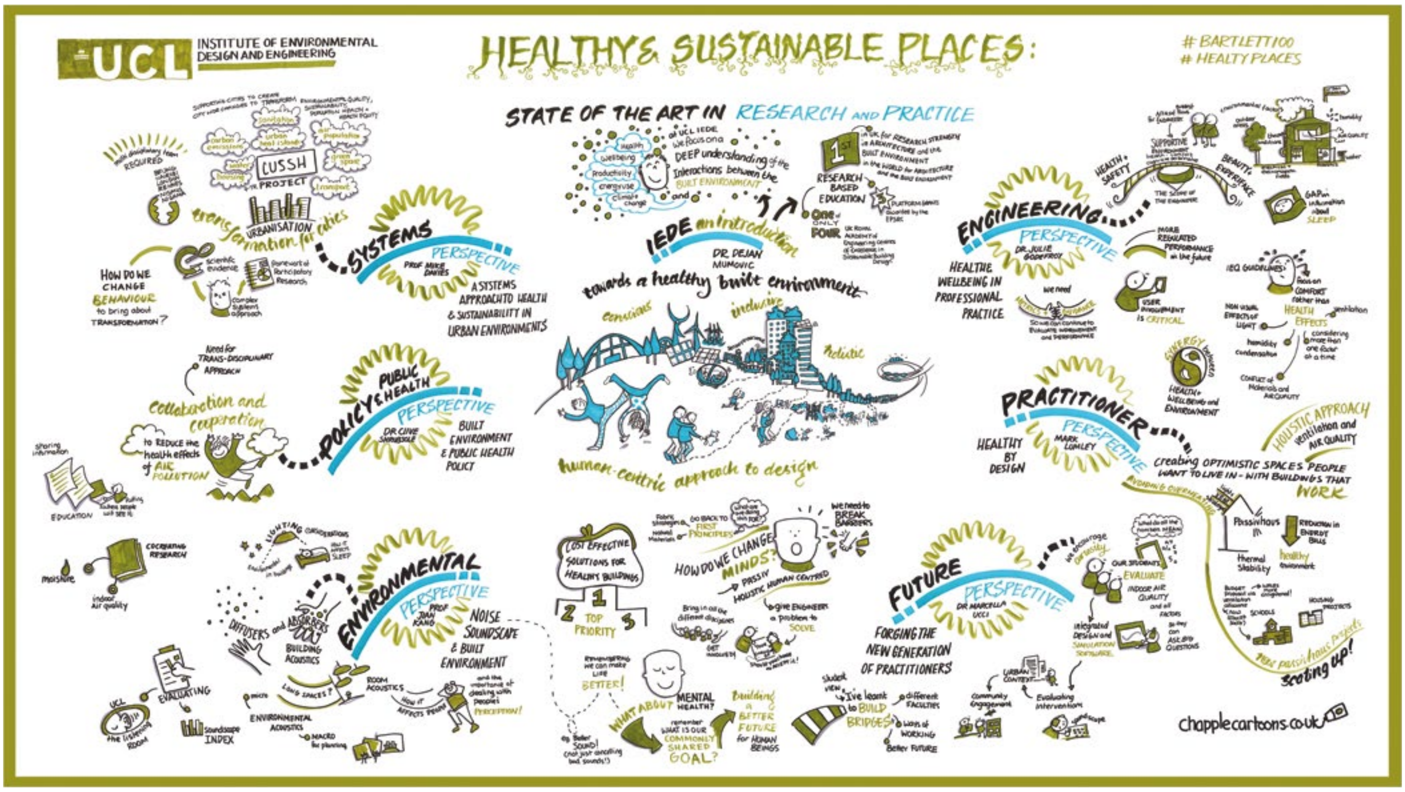
We began the walkthrough of the CLD with the central concept of sustainable decision-making and policy implementation. This concept is not only influenced by systems thinking, but also supports the further embedding of systems thinking and transdisciplinarity into policy- and decision-making. This dynamic forms the reinforcing feedback loop 'R3: systems thinking and transdisciplinarity', which becomes increasingly effective once initial implementation of systems-thinking and transdisciplinary approaches occurs.

In summary, first, Figure 2 shows two large feedback mechanisms that are shared among many UCL IEDE Research Themes, illustrating how the effects, value and health impacts of measures can drive improved data generation and decision-making. However, the reinforcing nature of some of these processes underscores the critical need for initial evidence and momentum – key focus areas of our Research Themes. Second, Figure 2 also shows that these efforts influence many aspects of buildings and their surroundings, showcasing potential positive impacts alongside exemplified notable unintended consequences. The following sections delve deeper into connections with Planetary Health, the Themes' evolution in UCL IEDE, as well as synergies across Themes, methods, scales, focus and outreach.

Themes as an expression of 'Environmental Design and Engineering' for Planetary Health: Our Themes express the complex nature of 'Environmental Design and Engineering' in the 2020s, particularly in its application to building design/operation and to various aspects of the built environment. For a start, the term 'Environmental Design and Engineering' is in itself complex. It can refer to the design or management of key factors related to the way(s) in which aspects of environmental quality (EQ) – especially air, temperature, moisture, light and sound – affect people in buildings and cities. However, more broadly, the discipline is rooted in design and engineering approaches to preserve – and ideally enhance – people's health and wellbeing, while protecting the environment. Inevitably, the expertise and research needed to address this dual-purpose agenda means that, at times, more focus is given by some researchers/Themes to one aspect (e.g. net zero, lifecycle approaches) versus the other (e.g. how EQ affects health/wellbeing). Nonetheless, the discipline is well positioned to deliver built environment responses to the major societal challenges central to agendas such as 'Planetary Health' (Whitmee et al. 2015; Walton 2019). These agendas focus on tackling environmental degradation, social inequity and threats to public health, by addressing the deep interconnections between the health of our species, all other living organisms and the planet itself. While 'design' and 'engineering' are cornerstones of our activities, inter- and transdisciplinary working within a systems-thinking framework are increasingly important. Indeed, our staff have a variety of academic backgrounds, ranging from architecture, engineering, physics, geography, economics and business.

An evolving agenda: For a considerable time, our research has addressed long-established aspects of EQ – for example, moisture, temperature and lighting – whereas acoustics and soundscape were added to our research portfolio more recently (~2018). In parallel, the pursuit of energy efficiency – especially on the demand side – has also been a cornerstone of our research, with net zero being its natural evolution, under the context of climate change. It could be argued that our research has evolved under the context of three fundamental drivers:

- Environmental degradation, with climate change mitigation and adaptation being key.
- Environmental, social and health inequalities, exacerbated by environmental degradation and social injustices embedded within the built environment.
- Widespread applications of artificial intelligence (AI) and the Internet of Things, providing new opportunities to harness and analyse data, and to identify new solutions for addressing environmental degradation and inequalities – while raising concerns about inclusion, equity and ethics.



Visual Summary of the Healthy and Sustainable Places Symposium, Bartlett Centenary Event (Image credits: Visuals by Caroline Chapple, on behalf of the UCL Institute for Environmental Design and Engineering (UCL IEDE), at The Bartlett Faculty of the Built Environment).

These contextual drivers have not only deeply affected the evolution of our long-standing Themes, but also spearheaded the 'birth' of three of our relatively new Themes. As nicely articulated in Chapter 4.6 (Smart Buildings and Digital Engineering), "The digital era has introduced new opportunities for developing and applying innovative modelling tools and research methods and for facilitating access to and utilisation of diverse data on buildings, building systems and occupants" (see page 195). Indeed, their research focuses on data-driven smart buildings, knowledge and tools for the digital delivery of buildings (e.g. building information modelling, or BIM), and advanced building and system modelling, which include a combination of machine learning and building physics approaches. Crucially, the underlying drivers for the Theme's advanced modelling and for digital and smart approaches are in some aspects aligned with the environment–health nexus, as applied to: building operation optimisation, fault detection and diagnostics, demand response and grid-interactive buildings. The second newest Theme – Life Cycle Assessment and Circular Economy – is perhaps one of the most notable 'departures' from the original focus on energy demand in use, and reflects a greater appreciation that embodied carbon and circular design are needed to truly tackle the risks associated with environmental degradation. It should be acknowledged that the focus on embodied and lifecycle impacts has been enabled, at least in part, by great strides in operational energy reduction. Finally, it could be argued that the drivers mentioned above are also directly related to the third newest Theme – Climate Change, Sustainability and Cities. The latter cuts across all other Themes, as it represents the context within which much of our research is positioned. Being so broad, admittedly our research does not cover every aspect related to climate change, sustainability and cities. On the other hand, such a broad Theme is also an opportunity to capture research which does not uniquely fit under other Themes – for example, aspects related to resources other than energy (such as water; see the CAMELLIA project: www.camelliawater.org) and addressing a range of sustainability objectives, in addition to carbon emissions reduction and comfort/health (e.g. the CUSSH project mentioned later).

Perhaps the 'newest' Theme, both chronologically and conceptually, is the Systems Thinking and Transdisciplinarity Theme. It reflects how systems thinking, defined in Chapter 4.9 as "a skill, a way of thinking and approach focusing on interconnections, non-linearities, and understanding patterns of complex system behaviour and synergies", complements our research. This description – as a skill, a way of thinking and an approach – is also applicable to the notion of transdisciplinarity, an implementation-oriented integration and co-creation of knowledge and methods, which fits our research philosophy well. Crucially, transdisciplinarity also means that diverse disciplines and stakeholders have an equal say in what is important and in the challenges/opportunities associated with identifying how to address difficult problems, such as those which our research aims to tackle in the built environment. The relevance and value of systems thinking for our research is also demonstrated by the willingness and ability of UCL IEDE researchers to engage with system dynamics and co-produce a CLD for each Theme's chapter with experts in the field.

Synergies across Themes: While our Research Themes are instrumental to activities within and outside UCL IEDE, their delineation is in some ways artificial. Themes are connected, with important overlaps across activities and people involved in them. For example, Chapter 4.2 (Light and Lighting) highlights: "Technological advances, such as LEDs and smart lighting controls, have reduced resource use for lighting (in terms of lumen/watt); however, there is a growing necessity to assess the lifecycle of buildings, […] highlighting a shift from operational energy to a wider approach considering the entire lifecycle and embodied carbon of buildings, and incorporating circular choices in design" (see page 143).

More broadly, at the core of much UCL IEDE research is the need to reduce energy use and carbon emissions in buildings and cities, while fostering health and wellbeing for all, including the most disadvantaged. In this sense, Themes such as Energy Use, Retrofit and Net Zero Carbon are highly complementary to Themes related to EQ parameters. In turn, the latter are strongly linked to climate change mitigation and adaptation. These links are clearly expressed in Chapter 4.8 (Energy Use, Retrofit and Net Zero Carbon): "[Future-fit and inclusive retrofit strategies] must consider the inter-relationships between mitigation and adaptation goals and respond to the projected evolution of building stock and occupants" (see page 224). Furthermore, the issue of 'heat' – now and in future – and associated risks at building and urban scales are a recurrent topic across several Themes, and one where the impact of our research is evident. At the same time, while some Themes have a stronger focus on certain methods (e.g. advanced modelling, participatory methods), these are also utilised and referred to in other Themes. It should also be acknowledged that some research projects are mentioned by several Theme chapters. This reflects in part the breadth in scope of those projects, but also the synergies across Themes and the complementarity of the UCL IEDE community's skills and interests. These overlaps also evidence our critical mass and capacity in some research areas, particularly for some of the broader or most established Themes.

Methods: Our research is underpinned by two key approaches. Firstly, we use and/or develop advanced models of building/environmental performance at the building and urban scales. This includes building stock modelling, geospatial analysis of energy/carbon and environmental conditions, and how EQ factors (e.g. light, sound, air quality) affect health and wellbeing. Secondly, modelling is complemented by an equally strong focus on field and lab studies – which heavily rely on, and benefit from, capital assets such as the environmental, lighting and acoustics chambers at UCL East and from ownership/access to high- and mid-grade portable monitoring equipment. These two pillars – modelling and monitoring – are accompanied by relatively newer methodological additions, which cut across several Themes: i) harnessing machine learning, AI and data-driven approaches; ii) systems thinking and system dynamics; and iii) qualitative research. There is also an increasingly strong emphasis on transdisciplinary working, participatory approaches and celebration of diversity in the creation of knowledge and solutions/methods. This is well expressed in Chapter 4.9 (Systems Thinking and Transdisciplinarity): "As our work has shown that practitioners find the complex and divided language used across disciplines difficult to navigate, we will focus part of our efforts on capacity and capability strengthening. This would mean developing accessible language and easy-to-use tools that resonate with individuals' and organisations' existing experience. […]. True to the co-creative identity of our group, we want to keep celebrating this diversity" (see page 237).

Scale, focus and outreach: The Themes' chapters clearly showcase research at building and urban scales, with considerable outreach and impact nationally (within the UK) and internationally. Complexity and systems thinking cut across all Themes. This clearly reflects the nature of the research field but also demonstrates the legacy of three successive Engineering and Physical Sciences Research Council (EPSRC) Platform Grants awarded to the group, as clearly articulated in Chapter 4.9 (Systems Thinking and Transdisciplinary): "The first Platform Grant supported the recognition of complexity in the built environment, and the second Platform Grant focused on the unintended consequences arising from this complexity. The third Platform Grant emphasised systems thinking to address such unintended consequences and aimed to transform scientific understanding of the systemic nature of a sustainable built environment" (see page 237).

At the building scale, our research has evolved from a focus on building design to discussing the need for better understanding and integration of occupant needs/behaviour (performance gap), and more broadly to evaluating building performance throughout the building lifecycle. For example, as mentioned in Chapter 4.8 (Energy Use, Retrofit and Net Zero Carbon), the 'Total Operational Performance' collaborative project between UCL IEDE and Tsinghua University – funded by the EPSRC (UK) and the National Natural Science Foundation (China) – investigated the problem of the performance gap in energy performance and indoor EQ in schools, offices, hospitals and residential blocks in the UK and China. This led, for example, to the publication of the Chartered Institution of Building Services Engineers (CIBSE) Technical Memoranda 61–64 (CIBSE 2020a–d).

As for building typology, our work focuses especially on homes and schools, with some research on workplaces – especially offices – and, increasingly, care home settings. Leadership in residential and educational settings is evidenced by UCL IEDE's state-of-the-art modelling platforms on homes and schools. Our UK housing stock model has been developed, calibrated and applied over many years (e.g. Symonds et al. 2016; Taylor et al. 2019; Petrou et al. 2024). The tool is capable of modelling indoor environmental quality in millions of homes at postcode level under various climate and retrofit scenarios. Our Modelling Platform for Schools (MPS) (Schwartz et al.

2022) is a 'one-by-one' school building stock model which currently simulates building characteristics and indoor temperature across all 65,000 schools in England (see Godoy-Shimizu et al. 2022). The MPS has had national outreach. It has been used to establish the carbon baseline for English school building stock (with Deloitte) and to highlight the overheating challenges of climate change (with the Met Office) and decarbonisation pathways (with Mott MacDonald) – resulting in the world's first report on decarbonisation strategies for English schools in the context of climate change and cognitive performance. At a national level, Prof. Mumovic will also be able to make a positive impact as newly appointed Scientific Advisor for Decarbonisation and Climate Change to the Department for Education.

Our modelling and data-driven work at a building typology scale includes international outreach. For instance, we have actively contributed to the International Energy Agency (IEA) Energy in Buildings and Communities (EBC) programme. This involvement has contributed substantially to Annex 81 on Data-Driven Smart Buildings, and included us co-leading a sub-task (International Energy Agency 2020). International collaboration on defining and addressing the latest challenges in the built environment domain is also evidenced via participation in further IEA initiatives, including Annex 91 on Open BIM for Energy Efficient Buildings (International Energy Agency 2024) and Annex 82 on Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems (International Energy Agency 2022).

Our research also addresses urban-scale, national and international aspects. We address the urban scale, particularly in relation to lighting (e.g. artificial street lighting), soundscapes and heat, with some growing interest in other aspects such as pollution and green infrastructure. Transdisciplinary collaboration with stakeholders such as the Greater London Authority or housing associations has supported programme delivery at urban or neighbourhood scales. Research on heat is a particularly good example of how expertise at building and urban scales, as well as integration with systems analysis and transdisciplinary collaboration with diverse disciplines (e.g. public health) and stakeholders (including policy makers), has yielded impact at a national level. For example, UCL IEDE has contributed to multiple Climate Change Risk Assessments (CCRA) and is leading the Built Environment and Communities technical report chapter for publication in 2025. Of note, our work was a key factor in highlighting building overheating as the second most important climate risk facing the UK in the second CCRA (https://www.ucl.ac.uk/impact/case-studies/2022/apr/tackling-climate-and-health-risks-overheating-buildings). This led to the inclusion of building overheating in the 2018 National Adaptation Plan, and eventually led to the creation of overheating standards for new homes through the Future Homes Standard and Part O of the Building Regulations in England. Furthermore, UCL IEDE academics have also worked on the first in-depth analysis that holistically studied the UK's complex-to-decarbonise homes from a sectoral perspective, quantifying their significant decarbonisation potential, to underpin the Climate Change Committee's net zero advice to the UK Government.

Leading or co-leading research collaborations with academic leaders and key stakeholders in climate change, public health, sustainability and built environment has also achieved considerable outreach internationally. For example, the CUSSH (Complex Urban Systems for Sustainability and Health) (https://www.ucl.ac.uk/complex-urban-systems) was a Wellcome Trust-funded project (2018–2024) to deliver global research on the systems that connect urban development with population health. It had 13 partner organisations across six cities (London (UK), Rennes (France), Kisumu and Nairobi (Kenya), Beijing and Ningbo (China)), and developed pathways to improve population health and sustainability through participatory systems-thinking modelling processes. Examples of impacts include the integration of health and sustainability evidence in informing urban infrastructure investments, which influenced regional and national policies in Kenya. Further indicators of international esteem and leadership are UCL IEDE members contributing to The Lancet Countdown (Household Air Pollution Indicator led by Dr Nahid Mohajeri), which aims to monitor the health aspects of climate change through an annual assessment produced by an independent international collaboration (https://www.thelancet.com/countdown-health-climate).

Research Priorities and Agenda for the Future

Each of the eight Themes has outlined, in their respective chapter, the key research challenges and priorities in their field. Besides sector-specific aspects, some overarching ideas emerge. In addition, some issues mentioned by selected Themes may be of importance for the UCL IEDE research agenda as a whole. These aspects (cross-cutting and specific but transferable) are summarised below:

- How to effectively integrate energy efficiency/net zero with health/wellbeing objectives, particularly but not exclusively within the context of climate change mitigation and adaptation, was a key overarching priority for most Themes. In other words, a key priority is evaluating the co-benefits and unintended consequences of retrofit and net zero. One way of expressing this challenge and mission is outlined by the Energy Use, Retrofit and Net Zero Carbon Theme, whose chapter refers to the need for "new optimised decision-making approaches, developed with key stakeholders, should emphasise decarbonisation as a pathway to adaptation and climate equity".
- Health, wellbeing and comfort are key priorities for most Themes, with the need to find new ways and new evidence to characterise the relationship between built environment factors and health/wellbeing. Health and wellbeing were slightly less central for the Life Cycle Assessment (LCA) and Circular Economy Theme, although the environmental impacts evaluated through LCA approaches could eventually be evaluated also in terms of health and equity/inclusion.
- Data availability, quality, integration and associated ethics was identified as a challenge, and an opportunity, by most Themes. Going forward, UCL IEDE Themes could collaborate explicitly on this matter, as there are clearly considerable synergies across Themes, and complementary expertise.
- The research value of AI and data-driven approaches, including deep learning-based neural network models, was mentioned by several Themes, and indeed applications of these are utilised already across various current research projects.
- The role of existing and new technological solutions, particularly but not exclusively within the context of net zero (both new-build and retrofit), is mentioned by some Themes. These cover a broad range, including building materials and fabric, as well as solutions for energy supply at a building and district level, and for the decarbonisation of energy supply via renewables.
- The need to provide evidence and methods to emphasise the 'value proposition' of solutions is also important. This aspect is mentioned, for example, in Chapter 4.6 (Smart Buildings and Digital Engineering), in relation to the business case for 'digital solutions', but also in a different context in Chapter 4.5 (Climate Change, Sustainability and Cities) (in relation to urban green infrastructure), and in the Acoustics and Soundscapes Theme, regarding the 'value' of urban soundscapes for public health. To some extent, this aspect – how to approach the 'value proposition' – is also related to the need to communicate complexity effectively, and more broadly to accept and celebrate diversity in understanding approaches across stakeholders - which are referred to in the Systems Thinking and Transdisciplinarity Theme.

In summary, in the next decade the research agenda for UCL IEDE is likely to move beyond its current knowledge-oriented vision – that is, to "pursue a deeper understanding of the interactions between the built environment and health, human wellbeing, productivity, energy use and climate change" (https://www.ucl.ac.uk/bartlett/environmental-design/). Rather, overall, the Research Themes have expressed an action-oriented vision to foster transformative change in the built environment, for the integration of health and wellbeing objectives with climate change mitigation and adaptation goals, by leveraging digital and data-driven innovation framed by sustainability, systems thinking and transdisciplinarity.

Acknowledgements

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East London (image credit: IEDE staff)

THEME: LIGHT AND LIGHTING

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1. Where We Are

When Richard Llewelyn-Davies became Head of The Bartlett School of Architecture at University College London in 1965, he appointed RG Hopkinson as Chair in Environmental Design and Engineering, a position jointly funded by GN Haden and the Pilkington Brothers. Lighting research at The Bartlett began with this appointment. Hopkinson's research ranged from investigations into the luminance distributions of road lighting installations to visual discomfort as well as brightness and its effect on the visual environment. Hopkinson was joined by Jimmy Longmore with whom he had worked to propose the split-flux method, an empirical formula for calculating the Internally Reflected Component of the Daylight Factor.

The newly formed Environmental Research Group in The Bartlett was later joined by Ted Rowlands and David Loe, who published research into visual performance, colour rendering and characterising the appearance of lighting in rooms. Kevin Mansfield then joined the team and built on this work in his PhD thesis, entitled 'Luminance Patterns in Buildings: Meaning and Design'. He also explored the effect of facade design on daylight in buildings such as hospitals and prisons. In 1987 the team established the MSc Light and Lighting course which, while providing an advanced degree education in lighting, has also been used as a vehicle to disseminate the group's lighting research. The proof of its success is that its graduates went on to lead some of the most influential companies in the industry – for example, Florence Lam at Arup, Desmond O'Donovan at DHA Designs and Richard Caple at Thorlux. The influence of the MSc Light and Lighting course also permeates into academe, where, for example, Michael Rohde led the lighting programme at Hochschule Wismar.

Peter Raynham joined the group from Philips Lighting in 1996 to design and execute the Candle 1 project, an architectural workbench tool that provided a front end to Radiance. The idea was to put Radiance into an existing architectural tool, and this was used by Alan Penn's group in the recently formed Centre for Advanced Spatial Analysis. The Candle 2 project followed – a simulation tool for outdoor lighting, which enabled roads with houses on either side to be modelled and real road lighting installation distributions to be depicted with photometric accuracy. These simulation tools were cutting-edge at the time of their development; however, they have since been replaced by a plethora of commercially available lighting simulation tools. Peter Raynham also built the SkyLab (Figure 1), which was first commissioned in 1998, and is used for teaching and research. Notable industry clients who have used the facility include Nicholas Grimshaw, Michael Popper Associates, Max Fordham, BDP and WSP.

Figure 1. SkyLab at UCL Here East (Image credit: Edward Barrett)

MERLIN: Mesopically Enhanced Road Lighting, Improving Night-vision (collaborations between UCL and City and Sheffield universities). The main findings of the Glare project were that veiling luminance has a significant effect on visual performance; that, in a laboratory context of relatively high contrast, less glare sensation is reported by older compared with younger people; and that the sensation of discomfort glare corresponds to activity in regions of the brain identifiable using fMRI. One key finding of the MERLIN projects was that patterns of view change after dark due to reduced saliency in the peripheral visual field caused by low contrast. Another was that street lighting patterns affect pedestrian reassurance.

Edward Barrett joined UCL on the Glare project and Jemima Unwin Teji was part of the Sheffield branch of the MERLIN project, joining UCL following completion of the project. The lighting team consists of five more tenured staff members: Tad Trylski, Stephen Cannon-Brookes, Cosmin Ticleanu, Mandana Khanie and Farhang Tahmasebi, bringing expertise in lighting design, computational design, vision, applied research and daylighting.

Apart from scientific research projects, the group has enjoyed a wide range of consultancy projects – for example, studies on the impact of photocell choice on energy use; visibility in underpasses and short tunnels; the writing of the Energy Performance of Buildings Directive, the Pocklington Trust Guide to Lighting for People with Sight Loss and the Society of Light and Lighting's Lighting Guide 2: Lighting for Healthcare Premises, as well as 50+ British Standards relating to lighting. The Lighting Group has nurtured proactive and productive relationships with the main lighting professional bodies (Society of Light and Lighting, Institute of Lighting Professionals and International Association of Lighting Designers) and aims to continue to strengthen its symbiotic relationship with industry. The group benefits from long-term, valuable teaching input from industry stalwarts – for example, Mike Simpson, Global Lead for Lighting Design at Signify; Ruth Kelly Waskett, Daylighting Lead and Project Director at Hoare Lea; Carolina Florian Valbuena, Vice-President of the Society of Light and Lighting; and Alkestie Skarlatou, Director, Light in Space. Each year MSc Light and Lighting students participate in the Society of Light and Lighting's Ready Steady Light event, and in 2024 they won the Society's Technical Award for their installation 'March of Time' (Figure 2), which used a low-energy, lowglare, dark sky approach.

Figure 2. 'March of Time' installation and the winning UCL team, with Dan Lister, SLL (Image credit: Edward Barrett)

2. Research Challenges

2.1 Reducing energy consumption while lighting for human needs

Illumination, as we know it, is undergoing significant changes and facing numerous challenges (Boyce 2005). The market for electric lighting and daylighting technologies is experiencing continuous growth. While reducing energy consumption and carbon emissions remains a top priority, enhancing the health, comfort and wellbeing of building occupants is becoming increasingly important (Boyce 2014). More fundamentally, light plays a pivotal role in orchestrating spaces that transcend physical boundaries and empowering individuals to perceive and experience architecture (Amundadottir et al. 2017). These objectives are shaping the way we approach lighting in the built environment. Despite our broader understanding of the perceived qualities of light (Figure 3), and our enhanced knowledge of human needs regarding light exposure, current design approaches only partially ensure the quality of lit environments (Begum et al. 2013; Lockley 2009). The performance gap between the design intent and the reality of implementation demonstrates that factors influencing the operation of the whole building system design remain poorly understood. If this is to be optimised, then multi-sensor interactions also need to be considered so that we can capitalise on them in the digital world.

Figure 3. Demonstrating the intrinsic beauty of daylight in buildings (Image credits: Edward Barrett)

Another key challenge is understanding how we can make better use of daylight in buildings. Evidence suggests that to ensure human health (Boyce 2006) we need much higher light exposure during daytime than is typically received by the occupants of buildings (Bonavia et. al. 2023). If we are under-lighting buildings, then we need to know, so that we can propose interventions and design features to overcome this without dramatically increasing energy consumptions. A paradigm shift to an objective of 'maximum use of daylight in buildings' could create a path to correct the mistakes of the mid-20th century, when deep-plan buildings relied on electric lighting during daylight hours. The health benefits of daylight are well known, and the extent to which electric lighting can provide health benefits is modest by comparison. However, there are still situations – for example, those of night shift workers – where exposure to daylight is limited. In these circumstances, analysing the health effects of light is extremely challenging given the multitude of confounding variables.

Aligning health and wellbeing with energy concerns necessitates better integration of daylight and electric lighting indoors. Overcoming the challenges posed by assumptions of 'optimum light' levels is crucial. Moreover, in recent years, working environments have shifted to a broader range of spatial typologies. This unprecedented situation has highlighted even more the importance of health and comfort indoors, with a shift in research towards better inclusion of human visual and non-visual needs in indoor spaces beyond offices (Mardaljevic et al. 2013). The future of illumination lies in balancing energy efficiency with the health of building occupants (O'Brien et al. 2020). By integrating advanced lighting technologies and controls, we can create environments that are not only sustainable but also conducive to visual comfort and productivity. This holistic approach to lighting will ultimately lead to more optimised and harmonious built environments.

2.2 Understanding the health impacts of the lit environment

WHO defines "health" as "a state of complete physical, mental and social wellbeing and not merely the absence of disease or infirmity". The inclusion of "well-being" in the definition of health is significant, because it means there are many contributing factors that are not related to lighting – for example, social and economic factors.

But light exposure can certainly influence human health. In addition to the well-established visual impacts of light exposure on health, there are also the more recently explored non-visual effects of light exposure. Access to natural light and a view has been shown to have health benefits and indirect benefits in terms of sleep rhythm, mood, productivity and comfort for building occupants, as well as effects on performance and productivity (Matusiak et al. 2024). Additionally, optimising the use of daylight significantly reduces visual discomfort and enhances occupants' wellbeing and appraisal of space. Excessive exposure to electric light due to a lack of daylight has a potential role in breast cancer. Exposure to the blue ranges of visible and ultraviolet (UV) light has several positive nonvisual biological health effects through circadian stimulation and triggering vitamin D generation in our bodies.

At the other end of the visible spectrum, near-infrared radiation (NIR) (Unwin Teji 2023) can penetrate deeper into tissues and has been shown to reduce inflammation, promote wound healing and improve cognitive performance (Powner & Jeffery 2024). Lack of NIR exposure can impair these beneficial processes, potentially leading to slower recovery from injuries, increased inflammation and reduced overall cellular health. Unless we are outside, we are exposed to significantly less red light and NIR radiation than historically was the case. This is due to technological advances over time, which have led to red- and NIR-producing light and heat sources being gradually removed from buildings. Examples are the coal fire, now rarely used to heat homes, the incandescent lamp, phased out since 2009 due to perceived inefficiency, and modern windows, which use low-emissivity glazing. The amount of red light and NIR in buildings depends on the levels outside, how much is being transmitted through windows, and the material properties of buildings and landscapes, inside and out. It is known that greenery reflects NIR (Figure 4). There is burgeoning industry and research interest into the effects of environmental red light and NIR.

Figure 4. Dappled sunlight seen through a tree canopy
(Image credit: Edward Barrett)

One challenge in this field is that the action spectra of the many potential human biological responses to red light radiation and NIR are not known because research in this field is in its infancy. However, given our evolutionary history, it is likely that exposure to red light and NIR in the environment could be beneficial to human health. Recent research has found that exposure to low levels of red light (670nm) can reduce the severity and onset of myopia in children. Myopia has proliferated in the last 50 years, and this trend coincides with legislation designed to improve the energy efficiency of buildings. Myopia in children can have serious consequences when they reach 40 or 50 years of age because it can lead to conditions such as macular degeneration and retinal detachment, with serious consequences for sight.

2.3 Building performance through the facade

While maximum daylight is desirable in buildings (Mardaljevic, Heschong & Lee 2009), there are several new challenges created by modern architecture, which often employs glazed facades. Excessive exposure to daylight could cause glare and thermal discomfort due to overheating. A proper and balanced combination of daylighting and electric lighting is a critical issue to address in a resource-efficient world. Defining proper illumination that will result in the maximum benefits of light for our visual and non-visual needs is an ongoing challenge because it is context-specific. So far, the majority of prediction models (Geraldine et al. 2021) for illumination conditions have been developed based on a combination of subjective responses. Visual functions such as contrast sensitivity and acuity, as well as visual system responses such as reflexive adaptation behaviour or gaze behaviour (Khanie et al. 2017), are often overlooked. These prediction models also neglect exposure characterisation to the broader spectral distribution of electromagnetic radiation outside of the visible range. Consequent to these major shortcomings, besides periods of discomfort and complaints, is the buildings' high and rising energy demand. This results from occupants' unpredictable and non-optimised interactions (Tahmasebi & Mahdavi 2018) with shading devices and electric lighting, accounting for 20% of global electric energy consumption. More importantly, loss of performance and unknown ageing consequences related to vision is risking occupants' wellbeing, with short- and long-term effects. A deeper and more objective understanding of the various behavioural factors affecting perception at the individual level is thus necessary to improve our ability to predict and evaluate daylighting and electric lighting conditions.

2.4 Interdisciplinary approach: Fostering multi-domain research

Another concern is that there is more to people's satisfaction with an indoor environment than lighting. This means that understanding the combined effects of indoor environmental factors – such as illumination, temperature, air quality and acoustics – on human behaviour and responses is essential for optimising building management and overall performance. These factors interact in complex ways, influencing not only occupant comfort and wellbeing but also energy consumption and resource efficiency. A multi-domain approach (Chinazzo et al. 2022) to building design is crucial for effectively balancing these interactions, allowing for a deeper understanding of how environmental conditions shape human behaviour. By integrating insights from various fields, this approach enhances the ability to create responsive, sustainable building environments that prioritise both energy efficiency and occupant health.

2.5 Lighting at the urban scale

There is an increasing demand for the use of outdoor environments after dark (Figure 5). As the nighttime economy continues to grow, street usage increases, which in turn fuels the economy due to heightened demand for transport and shops, including those small businesses serving the last mile home. Comfortable walking environments may be easily found in busy urban environments, where the presence of other people late into the night provides a sense of security (Erturk et al. 2024). Reduction in nighttime public services and the need to walk longer distances at these hours can create a sense of discomfort, especially for nighttime shift workers. Many others, including vulnerable groups such as the elderly and people with special needs, are affected by the onset of darkness to the extent that they do not consider taking public transport to social activities after dark. Perceived safety, or reassurance in an environment, is affected by the amount and uniformity of light, but other aspects, such as the effect of transitions between spaces and sensory processing disorder effects, are unknown.

Figure 5. An urban environment after dark
(Image credit: Edward Barrett)

Street lighting at night has the potential to influence two important public health outcomes: fewer traffic accidents and less crime. The outdoor environment changes appearance after dark, and with this change come additional vulnerabilities for street users, who may wonder whether they can be seen by drivers when crossing the road or whether dark areas provide hiding places for potential muggers. Building on earlier research, our recent research uses the clock change method to prove the extent to which ambient lighting conditions (daylight versus darkness) can influence actual crime, as opposed to perceived crime, to enable a first step towards understanding the effect that electric lighting could have. If a light change as drastic as daylight to darkness has no effect on crime, then the nuances of the various characteristics of electric light will not matter. However, if there is an effect, then we can understand the types of crime which are likely to be affected by lighting conditions. The PhD work of Ezgi Erturk has so far found a significant increase in dark compared with daylight periods for the crimes of theft from a person and robbery of personal property (Erturk et al. 2024). The challenge is that, while we know that lighting conditions do influence safety, we do not yet know all the characteristics of light that have an effect.

2.6 View

View is equally important at night and during the day. At night, the view is an important factor in both crime and traffic accidents. During the day, daylight and view should not be seen as separate entities, as we find meaning in the variation provided by daylight – with changes in time, direction and location providing us with essential information about where we are, what the time and day are, what is going on and, by implication, what are we expected to do. The challenge is how to approach this field when photometric measures alone can be poor predictors of glare because light carries information that matters to our response (Khanie & Andersen 2024). This is also a pertinent issue at night. Daytime view quality assessment is an active research area that has resulted in many attempts to categorise view quality. A key challenge is how to apply these findings to nighttime scenarios, when our needs and expectations may differ.

2.7 Policy and raising awareness

Research plays a critical role in enhancing our understanding of lighting effects. This understanding is of little value if it does not influence changes in lighting practice and policy. It is essential to influence policy to implement practical changes in building and urban design. Policies play a crucial role in shaping societal practices related to lighting and are often ‘game changers’ in driving significant change, particularly in building renovation and construction. The transformative impact of advances in technology, such as the widespread adoption of LEDs, has greatly reduced energy consumption by lighting. This shift underscores the need for updated policies that reflect the current state of lighting technology and its implications for energy efficiency. Identifying and addressing problematic policies, as well as recognising areas of tension, is essential. Meaningful policy changes are necessary for influencing practice, enhancing sustainability and improving lighting conditions for all.

3. Setting the Research Agenda

3.1 Energy

Lighting research is an ever-evolving interdisciplinary domain, as technology advances, electric light sources and control systems advance to allow better integration with architecture and between architecture and external conditions. Integrating daylight and electric lighting is a pathway that suggests the need for a more nuanced understanding. Current research assumptions often take daylight availability for granted, but there's a need to consider conditions dominated by electric light because daylight has become a rarer commodity as urban areas have become spatially more dense. Hence, a re-examination of the balance and integration between daylight and electric light is essential.

The energy theme in lighting research is typically driven by a desire to reduce costs by reducing energy usage. This can be met by good lighting design which considers the specific needs of the context by placing the right light in the right place at the right time, using the right control systems (ref. SSL Code). The interpretation of 'right' is subjective and requires competence on the part of the designer or engineer to interpret the needs of the specific situation. Two questions are often overlooked, and these will need to be considered in future research:

— Are people making the most of the light that they have?
— Are we under- or over-lighting?

There is no universal 'optimum' form of lighting due to site-specific and urban fabric-specific variables. The objectives of lighting should remain specific to the context and not be overly generalised. A pathway for characterising human needs, and lighting quality that addresses both physiological and psychological aspects of comfort and health, is essential.

3.2 Beyond domains and disciplines

Optimising daylight and electric light integration involves more than simply increasing daylight availability and addressing electric light in space; it requires addressing thermal comfort, energy efficiency and occupant behaviour (Figure 6). A holistic approach to building design is crucial for balancing these factors and understanding the interactions between daylight, electric lighting, public health, energy and resources. This systemic approach should consider the interdependencies between environmental factors and human behaviours, aiming to enhance both energy efficiency and human health. Such insights highlight the importance of interdisciplinary collaboration and continuous dialogue in creating sustainable, human-centric lighting and building practices.

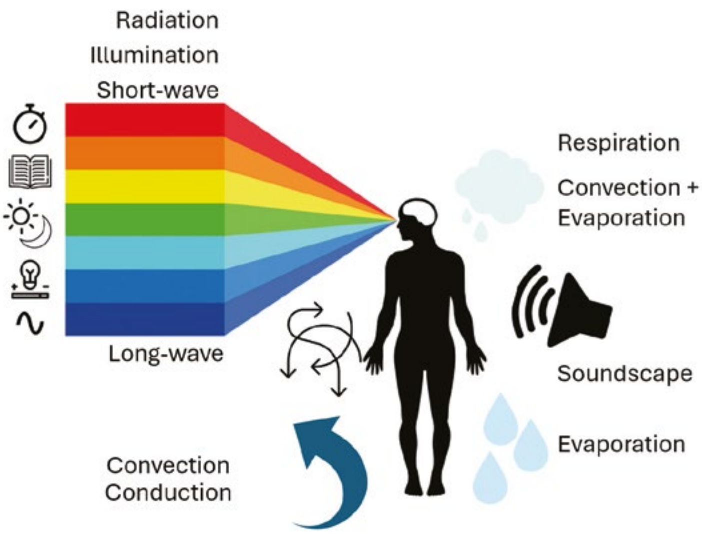


Figure 6. Summarising multi-sensory considerations beyond domains and disciplines (Image credit: Mandana Khanie)

We recognise that a multifaceted approach is needed in future research, balancing energy efficiency, human health and policy implications. Visual, thermal and acoustic environments, along with air quality, are four pillar aspects that tend to ensure the liveability of the built environment. This approach advocates for more research into how lighting affects human needs, including visual and thermal comfort, and interactions with building systems. Additionally, it stresses the importance of understanding the impact of lighting on mental health, beyond just visual and thermal comfort. It also highlights the need to explore control mechanisms, such as adjustability and user experience, and their impacts on other systems, including HVAC, envelope design, urban planning and the electric grid.

There is scope to collaborate with other groups to expand our knowledge of the relationships between and interactions of senses. Within the Institute for Environmental Design and Engineering, research into various aspect of indoor and outdoor built environment could be extended to consider luminance maps or 'lightscapes' and to explore the utility of this concept in lighting practice. An opportunity for research lies in understanding how lightscapes and other indoor and outdoor environmental exposures are interconnected on human response. The research group is addressing the research challenges in interdisciplinary, multidisciplinary and transdisciplinary approaches. We are crossing institutes to uncover the fundamentals of human needs in built environments where complex visual and beyond-visual human responses dominate multiple aspects of human health. In this group, we are addressing the integration of daylight and electric light, the controls where human response is considered a pivotal decision maker in control algorithms for more energy-efficient lighting solutions.

3.3 Decarbonisation, energy, resources and the circular economy

While integration of all the environmental factors and the human responses to them is essential to improve design in specific contexts, there is also the 'big picture' to consider. Specifically, there is a growing need to assess the lifecycle of buildings, particularly focusing on embodied carbon. Technological advances, such as LEDs and smart lighting controls, have reduced resource use for lighting (in terms of lumen/watt); however, there is a growing necessity to assess the lifecycle of buildings, particularly focusing on embodied carbon, as operational energy becomes relatively less significant due to the green transition.

With energy grids becoming greener, we must emphasise the importance of other drivers beyond energy efficiency. Utilising cutting-edge technologies, environmental measurements and artificial intelligence (AI) is essential. The entire lifecycle of energy and resource inputs, from extracting, manufacturing and packaging to transportation, installation, maintenance and disposal (end-of-life emissions), should be accounted for. These points underline the evolving priorities in building sustainability, highlighting a shift from operational energy to a wider approach considering the entire lifecycle and embodied carbon of buildings, and incorporating circular choices in design.

3.4 Human health factors

Investigating the impact of lighting on human health factors increasingly involves collaboration with other specialised disciplines, particularly the fields of biology, chronobiology and neuroscience. One of many good starting points in terms of the built environment specialism would be to investigate the spectral distribution of light indoors and outdoors, and to relate this to possible impacts on the prevention of various deficiencies and disorders such as myopia in children. Future work could also investigate the characteristics of light at the boundary at which light from the environment, whether it be indoors or outside, can have health effects as pronounced as improving metabolism.

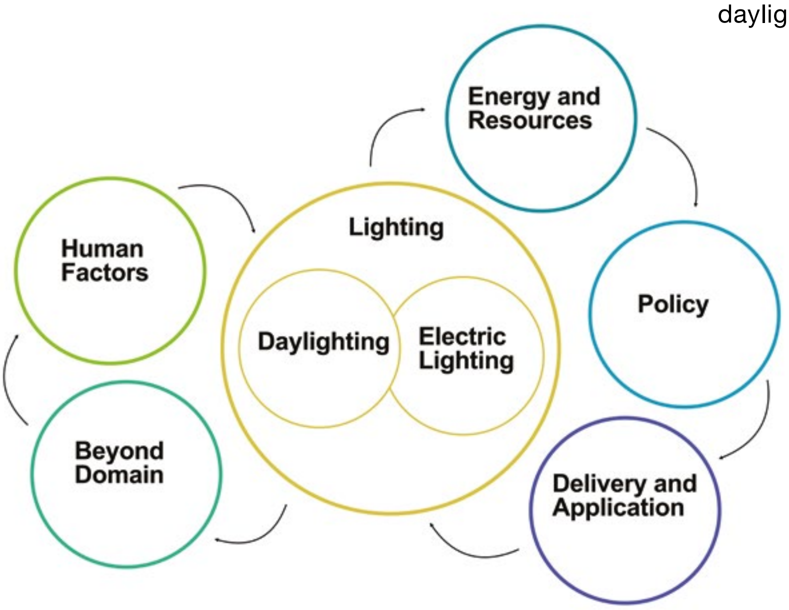
Work on the biological effect of the spatial distribution of light, measured at the eye level (Khanie et al. 2017) and by pupil size (Bonavia et al. 2023) has great potential. Developing the findings into applicable tools, which can be used by lighting designers, would help bridge the gap between research and practice.

Variations in visual disposition
Understanding visual performance and its importance has been a major area of research for over a century. This extensive body of work reveals that visual performance varies widely due to individual differences, ageing, health, occupation and life history. However, the emerging frontier is understanding the impact of light on human

health, a complex and still-developing relationship. Future research should explore how light affects human health differently from visual performance, acknowledging that light influences the development of babies and children, adding a layer of complexity to our understanding of its effects on humans. Individual differences are even more apparent in old age, and given the ageing Western population, further study of the effect of light on the health of the elderly would be timely.

The field of thermal comfort uses the term 'thermal disposition' to characterise the differences between people's self-assessed resilience to temperature. This idea could be expanded to visual disposition, building on existing research (Hemphälä et al. 2021) to identify and evaluate factors in the visual environment that may cause problems. Lighting PhD student Ruoxi Yin is currently exploring the effect of colour on the neurodiverse, because neurological diversity could impact our environmental sensitivity. A wide range of variations in visual capabilities and interpretation of experiences help build a case for a light sensitivity test for visual disposition.

Figure 7. Summarising the relationship between the factors discussed so far. The research agenda changes as new evidence manifests; however, the above themes pervade all future lighting research to varying degrees, depending on the project (Image credit: Mandana Khanie)



3.5 Policy

Recognising the critical role of policy as a game changer in society is essential for advancing lighting and daylighting practices. Policies must address problematic areas and tensions, ensuring they support practical changes like renovating existing buildings and constructing new ones with improved lighting strategies. The impact of technological advances, such as LEDs, has significantly reduced resource use for lighting (in terms of lumens per watt), shifting the focus towards human response aspects. Therefore, it is crucial to emphasise the importance of policy in driving these changes in building practices, to achieve sustainable and human-centric lighting environments.

3.6 Delivery and application

Raising awareness in the lighting field, including daylighting, involves multiple strategic actions. Firstly, it is essential to continue developing and promoting best practice lighting guidance and standards. Increasing public awareness about our sensitivities to light and the resources light uses can help individuals and organisations make more informed decisions. Additionally, it is important to highlight the indirect impacts of lighting strategies, such as their effect on embodied energy, to ensure a comprehensive understanding of their environmental footprint. Through these efforts, we can foster a more informed and conscientious approach to lighting design practice, ensuring successful integration of electric lighting and daylighting practices (Figure 7).

AI and lighting controls
Taking advantage of cutting-edge lighting technologies, measurements and AI tools and technologies is essential when it comes to advancing lighting design, research and practice. AI is only as good as the data available to the algorithm, and the key question is: how can we shape this? There may also be ways of bringing citizens into scientific research on a city-wide large scale, through the use of apps on their mobile phones.

There is a pressing need for a deeper understanding of individual preferences and requirements. This involves developing flexible, adaptive and personalised lighting solutions for indoor environments. Such systems should be capable of adjusting to the specific needs of each person, providing optimal lighting conditions that enhance comfort, productivity and overall quality of life. By focusing on personalised illumination, we can ensure that lighting technologies not only illuminate spaces but also contribute positively to occupants' wellbeing. One essential aspect of this is the consideration of variations in visual disposition.

3.7 Employing epidemiological approaches

While our lighting research has typically been focused on psychophysical experiments, we hope to continue to appraise the effect of lighting conditions on a large scale, using existing extensive datasets, in order to understand how human behaviour plays into the building and urban use. Using the example of outdoor lighting, this approach has the potential to provide wider society benefits, such as:

Improving pedestrian reassurance
Physical safety is not the only issue – people should also feel comfortable walking in cities at night. The whole luminous environment matters to this, not just the luminance of the road. Lighting conditions on the ground can be calibrated with satellite images to further investigate how, when and where lighting conditions affect pedestrian flows.

Increased safety
Understanding the effect of street lighting on nighttime footfalls has potential to impact local business, as increased footfall contributes to increased economic activity.

Increased connectedness
Light can also affect our interactions with society. New street lighting installations are increasingly controlled centrally and digitally. Remote control is easy to implement; however, there are many questions regarding what to do with the flexibility that centralisation offers. The aim of our research in this field should be to ensure that street lighting decisions do not result in inadvertent social exclusion.

3.8 Functionality and aesthetics

"The cloud that passes over gives the room a feeling of association with the person that is in it, knowing that there is life outside of the room … So light, this great maker of presences, can never be . . . brought forth by the single moment in the light which the electric bulb has. And natural light has all the moods of the time of the day, the seasons of the year, year for year, and day for day are different from the day preceding." – Louis I. Kahn

While the growing interest in seeking accurate luminous measurements (Lo & Steemers 2020) and the need to develop lighting codes and standards to monitor indoor light levels and maintain public health date back to the early 20th century, the story of lighting, and in particular architectural lighting, stretches back to the dawn of civilisation. Light plays a significant role in revealing architecture that stimulates senses, activates memories, and awakens feelings and emotions. As a key element in aesthetic design, both architecture and luminaires, it is important to understand not only its quantitative aspects but also its qualitative aspects. Lighting quality is a highly complex area of research in part because it involves higher-order perceptions. It is challenging to gauge subjective judgements and perceived lighting qualities (Houser & Tiller 2003). Beauty is in the eye of the beholder. But what is lighting quality? How do we define it? Can we measure it? How can we measure it? A minimum illuminance of 500 lux achieved in a library reading area, for example, may suggest the space is functional with adequate illumination; however, it may not be aesthetically pleasing. Several attempts have been made to propose frameworks for evaluating lighting quality and perceptions (Cuttle 2015) – perceived adequacy of illumination, perceived brightness, perceived contrast and visual impression. Future research should emphasise their applicability, especially in real and complex architectural contexts. This will provide invaluable insights into occupants' needs and requirements and enable us to gain a better understanding of the performance gap and create meaningful architecture.

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UCL IEDE Lighting Workshop

UCL IEDE lighting workshops

Dr Jemima Unwin Teji and Dr Mandana Khanie set the agenda of the workshops, which focused on future pathways of lighting research. They invited a diverse group of experienced specialists from the fields of the multi-modal indoor environment, daylighting, occupant behaviour, ophthalmology, environmental psychology, acoustics, public health and horticulture, as well as experienced lighting researchers such as Prof. Marilyne Andersen, Dr Rune Andersen, Prof. John Mardaljevic, Prof. Maria Johansson, Prof. Peter Boyce and Dr Jennifer Veitch.

Each workshop led to a structured discussion, bringing forth different perspectives based on the diverse experience and expertise of the group. The participants were very engaged and open in sharing their insights with a focus on driving refined, actionable and practical outcomes, which we were able to achieve in the form of this chapter and diagrams (including the CLD).

Table 1: Expert workshop 1 participants list

Name	Affiliation
Prof. Marilyne Andersen	Ecole Polytechnique Fédérale de Lausanne (EPFL)
Dr David Geisler-Moroder	Heschong Mahone Group (HMG)
Lisa Heschong	Heschong Mahone Group (HMG)
Prof. Rune Korsholm Andersen	Technical University of Denmark
Prof. John Mardaljevic	Loughborough University
Prof. Glenn Shrum	Parsons School of Design
Dr Jakob Strømann-Andersen	Henning Larsen Architects
Prof. Simone Torresin	University of Trento

Optimising daylight and electric light integration involves more than simply increasing daylight availability and adjusting electric light levels. It requires addressing a broader spectrum of factors, including thermal comfort, energy efficiency and occupant behaviour. A comprehensive approach to planning and designing buildings is crucial for balancing these diverse needs and understanding the interactions between daylight, electric lighting, public health, energy and resources. This systemic approach should consider the interdependencies between environmental factors and human behaviours, aiming to enhance both energy efficiency and occupant wellbeing. Such insights highlight the importance of interdisciplinary collaboration and continuous dialogue in creating sustainable, human-centric lighting and building practices.

The central question posed for the workshop was, “How does daylight and lighting in combination with other stimuli affect public health, energy, and resources?” The CLD presented included variables such as integrated daylight and electric lighting, public health outcomes, energy consumption and human needs. The goal was to critically analyse and refine this diagram to better capture the nuances of these relationships. Participants raised critical points about the definitions and scope of variables. For instance, the term ‘integrated daylight and electric lighting’ was scrutinised for its abstract nature, with suggestions to make it more quantifiable. The importance of distinguishing between residential and commercial settings and the contextual dependency of ‘optimum lighting conditions’ were also discussed.

1. Human needs and comfort: Consensus was reached on the need to place human comfort and wellbeing at the centre of lighting design, including visual and thermal comfort, mental health and occupant behaviour.

2. Commercial and business drivers: The role of economic incentives and market drivers in shaping lighting design was emphasised, highlighting the need to balance commercial interests with public health and environmental sustainability.

3. Energy efficiency and resource use: While energy efficiency remains crucial, the discussion acknowledged the shifting focus towards embodied carbon and the broader environmental impact of lighting systems.

4. Planning and policy: Effective planning and robust policies were identified as essential for driving change in lighting practices, with regulations and standards promoting sustainable lighting solutions.

5. Interdisciplinary research and education: The need for holistic, interdisciplinary research and education to address the complex interplay between lighting, human health and environmental factors was stressed, emphasising integration into academic curricula and professional training.

6. Technological and social innovations: Innovations in technology, such as advanced control systems for lighting, and social innovations, such as increased public awareness and engagement, were seen as pivotal for future advances.

In conclusion, the workshop underscored the complexity of integrating daylight and electric lighting in a manner that optimally balances public health, energy efficiency and resource use. The collaborative effort to refine the CLD and identify future research pathways highlighted the importance of interdisciplinary approaches and the need for continuous dialogue between academia, industry and policy makers. Addressing these multifaceted challenges requires a systemic approach to building design, considering the interdependencies between various environmental factors and human behaviours, striving for solutions that enhance both energy efficiency and occupant wellbeing. These insights provided a thoughtful conclusion to the workshop, reinforcing the importance of interdisciplinary collaboration and continuous dialogue in the pursuit of sustainable, human-centric lighting and building practices.

Table 2: Expert workshop 2 participants list

Name	Affiliation
Kristina Allison	WSP Global Inc.
Prof. Peter Boyce	Independent Higher Education Professional
Dr Annegret Dahlmann-Noor	Moorfield Eye Hospital, Honorary at University College London
Ezgi Erturk	University College London
Prof. Glen Jeffery	University College London
Prof. Maria Johansson	University of Gothenburg, Sweden
Dr Villian Lo	University College London
Dr Syam Mohan	UK Health Security Agency
Dr Celine Nicole	Philips
Dr Luke Price	UK Health Security Agency
Dr Julija Smyrnowa	Noise Adviser at Environment Agency
Dr Celine Villa	Gustave Eiffel University
Dr Jennifer Veitch	National Research Council Canada, Internation Commission on Illumination (CIE)

The round table was initiated with a brief overview of existing and past lighting research at UCL, and suggestions were invited which encompassed the main themes of the proposed CLD:

How to effectively complete lighting research that informs human health, whether this be via our biological system and/or our value system.

Physical safety – for example, safety from traffic accidents or crime – as well as social issues such as pedestrian reassurance.

How to approach practical matters such as using light to produce food and improve biodiversity, and issues such as the tension between useful versus obtrusive light/light pollution.

Three diagrams encompassing the work of the Research Theme were presented for discussion (early versions of Figure 8, Figure 9 and Figure 10). These precipitated an engaging discussion, and interesting key points which arose from the ensuing structured dialogue are outlined below:

1. Definitions and wider health: The importance of delineating wellbeing as a part of health, when discussing the effects of light. The social aspects of health should be considered too: the effect that light can have on the timing of our circadian rhythm can affect our interaction with society as well as our health.

2. Models, existing and new: The relevance of testing existing proposed models (such as CS, MEDI), as well as informing the fundamental research necessary to develop new models related to non-visual effects, particularly relating to long wavelength responses of the mitochondria (and others).

3. Consideration of individual variation: The necessity of developing frameworks to measure individual discomfort in the built environment, taking into account other sensory inputs and individual differences in discomfort thresholds, which change based on age, neurology and many other factors. Test and build on frameworks that others have developed, such as the Tranquillity Index and the Visual Ergonomics Risk Assessment Method.

4. Aesthetics and meaning: Pursuing research in the area of aesthetics, meaning and beauty despite the inherent difficulties caused by the subjectivity of the terms. These themes require investigation of motivations, expectations and behaviour, which, although complex, are valuable, because they relate to wider culture and sometimes religion.

5. Emotions and perceptions: The importance of other subjective issues, such as what contributes to pedestrian reassurance after dark. Emotions and perceptions are just as important as quantitative measures of crime and accidents counts in different lighting conditions. Physical safety is not the only factor that will encourage people to walk at night, and we should explore the whole luminous environment at night, not just the road.

6. Urban-scale studies: The necessity of the appraisal of light/dark in context and understanding how this plays into urban use. This should be examined at a large scale, employing citizen science and AI where the research method makes this feasible.

The three final diagrams, carefully refined following the discussion and used to inform the conceptual framework of the CLD, are presented below:

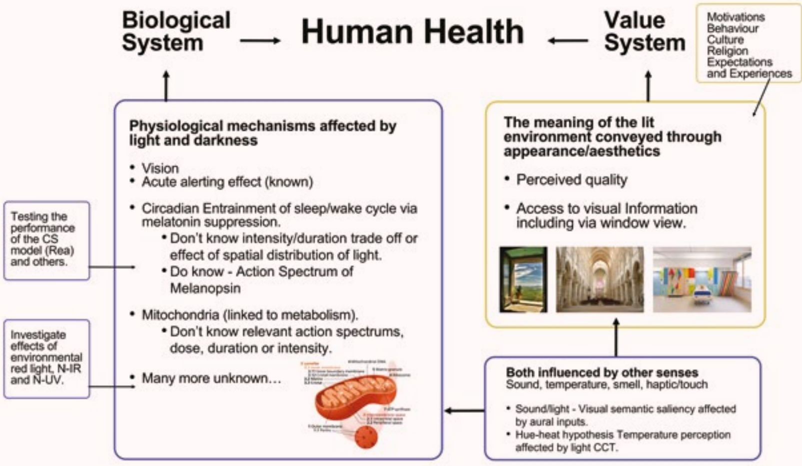

Figure 8. Diagram 1: Gaps in Lighting Research, pertaining to physical human health. Recognising physiological knowns and unknowns, some of which require fundamental biological research before the implications for the built environment can be investigated. The importance of our values to our health is implicit, and requires acknowledgement of the importance of our motivations, expectations and behaviour in our aesthetic judgements. In each case (physiological and psychological), vision does not operate in isolation and the interlocking effects of other senses on perception are of paramount importance (Image credit: Jemima Unwin Teji)

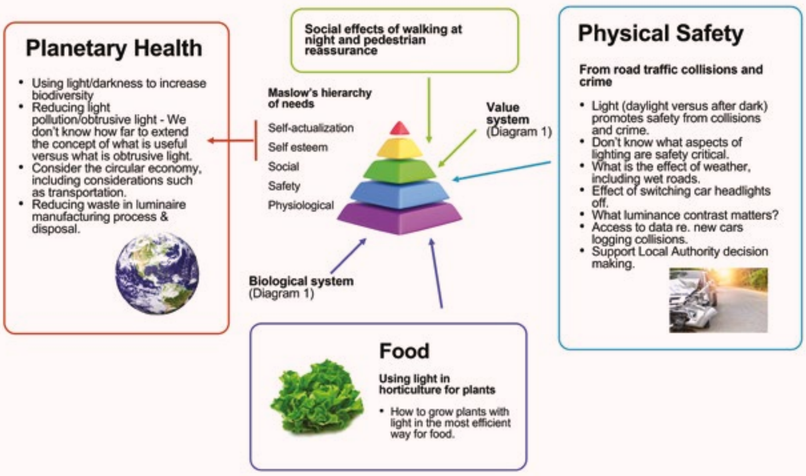

Figure 9. Diagram 2: Gaps in Lighting Research. Here, Maslow's hierarchy of needs is used to identify how lighting pervades each level. Apart for the physiological factors identified in Diagram 1, at a fundamental level, we cannot survive without food, and food requires light to grow. In terms of our physical safety, lighting has a large part to play, and there are still gaps in the literature regarding definition of the safety-critical aspects of light. Just as importantly, there are social implications of not feeling safe to walk at night to be considered. Once our basic needs are met, and in parallel to continued research in these areas, we consider the noble pursuit of caring for our planet in terms of reduced energy waste and increased biodiversity (Image credit: Jemima Unwin Teji)

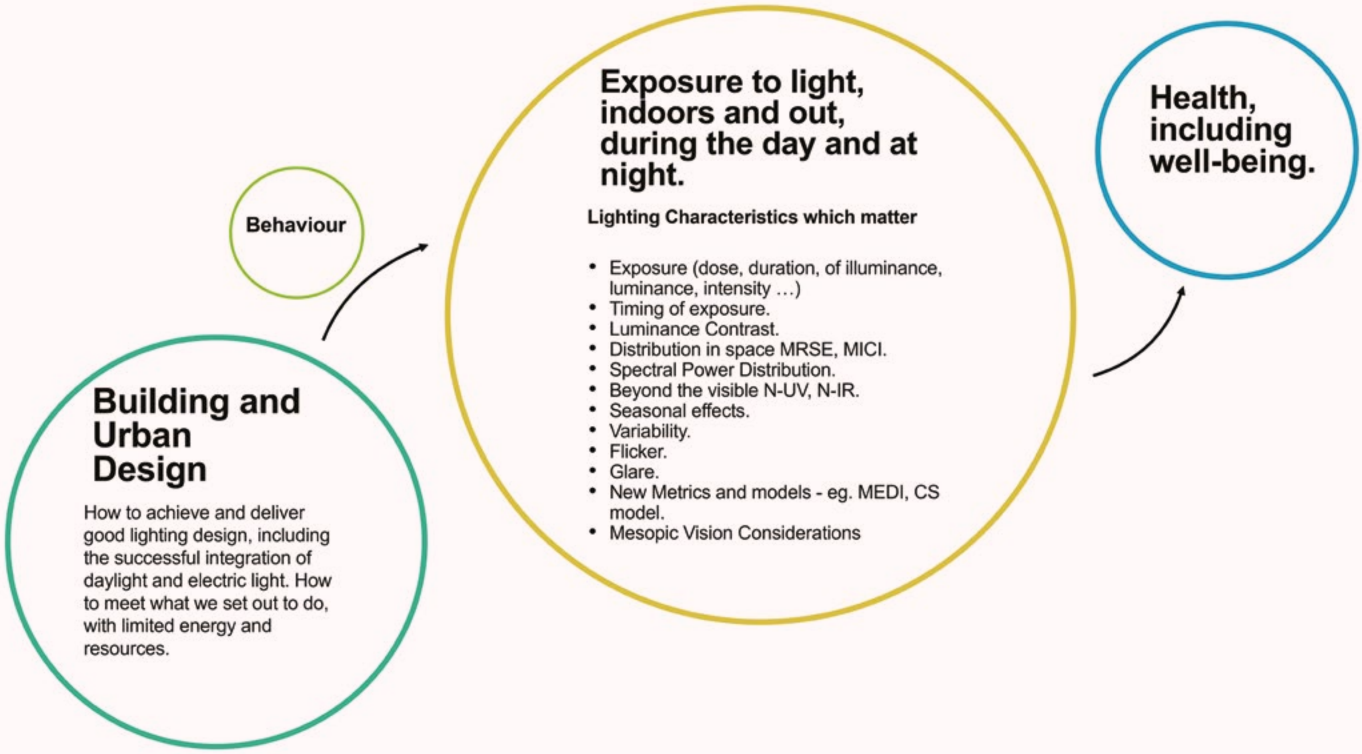

Figure 10. Diagram 3: Gaps in Lighting Research, identifying the many ways of describing light, and the effect of light, each of which is likely to inform an aspect of health. Fundamental to this are the environments in which we spend most of our time, indoors and out, and how we behave in these environments, which affects our exposure to light. The challenge is how to achieve the best lighting decisions for people, with limited energy and rescuers. Another challenge is that the answers to this question will be highly context-specific (Image credit: Jemima Unwin Teji)

UCL IEDE Light and Lighting Theme: Causal loop diagrams session

The final diagram focuses on two primary research gaps: "How do daylight and electric lighting, in combination with other stimuli, affect public health, energy, and resources?" and "What are the physiological and psychological effects of light on health and well-being?" The diagram illustrates variables related to the human response, broader comfort, health and wellbeing considerations, and combined sensory considerations and connections with climate and energy.

The diagram highlights several reinforcing feedback loops that play a critical role in optimising context-specific building system design. The increased integration of combined sensory elements in buildings enhances both natural and electric lighting. This integration improves the consideration of lighting quality in building design and optimises the appropriateness and intensity of light exposure for human physiology and psychology. As a result, this promotes appropriate human response patterns, improving both visual (R1) and non-visual (R2) health and wellbeing, which further facilitates the integration of combined sensory elements in building system design. Well-designed lighting supports the appropriate timing, duration and intensity of light exposure through both visual (R3a) and non-visual (R3b) routes. Such considerations can also apply to daylight equality (R4) in comfort, health and wellbeing. The integration of combined sensory elements in building system design also has the potential to enhance climate resilience, reduce overheating risks, increase comfort, health and wellbeing, and further promote the consideration of combined sensory elements in building system design (R5).

The diagram underscores the importance of a holistic and multi-sensory approach to lighting design that encompasses various aspects of human health and environmental sustainability for better and balanced building and building systems design. By addressing these interrelated factors, we can create built environments that are both energy-efficient and conducive to occupant wellbeing, ultimately fostering healthier and more productive spaces.

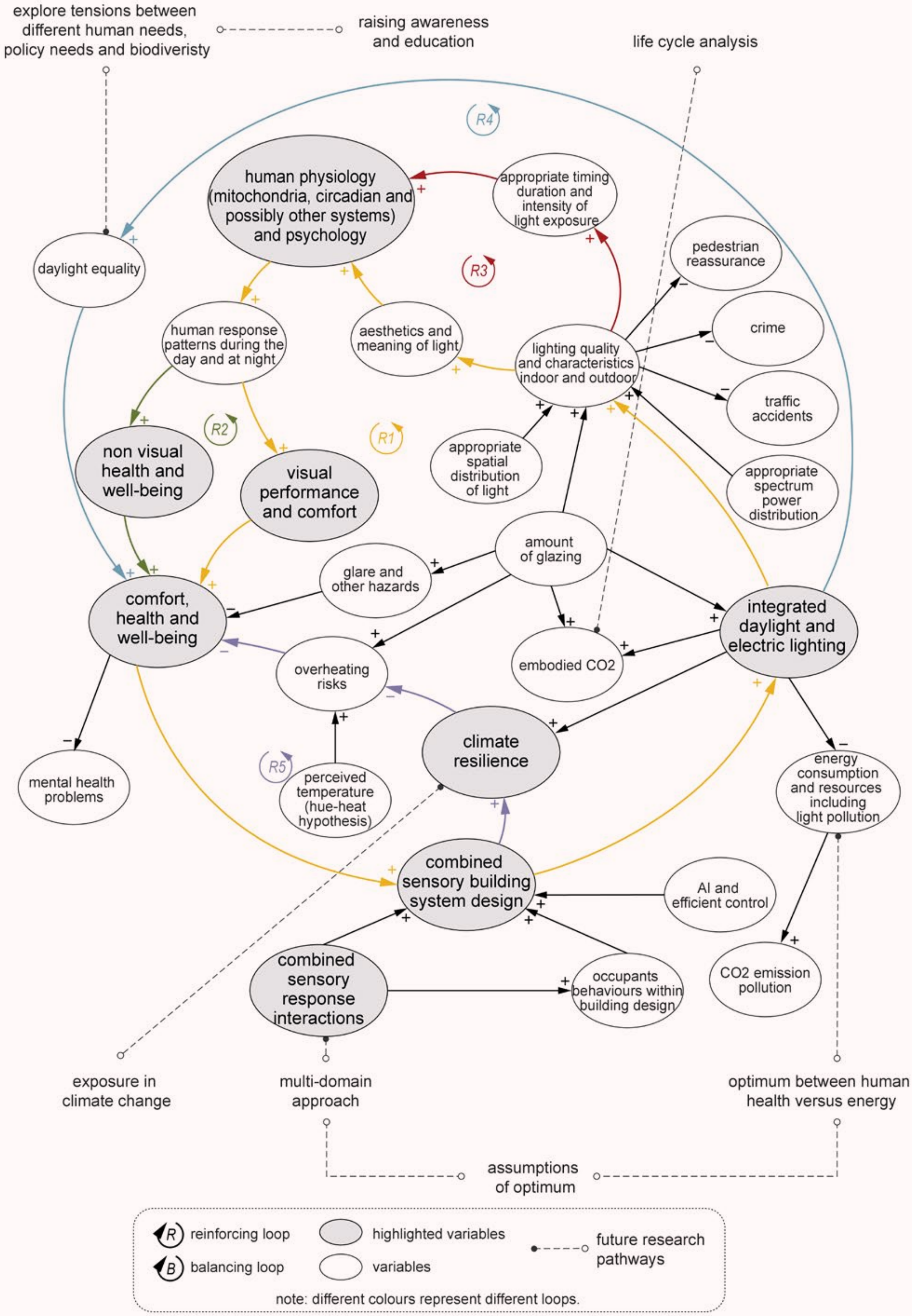

Figure 11. Causal loop diagram: Light and lighting
(Image credit: Koko Zhou & Daijia Ke 2024)

THEME: ACOUSTICS AND SOUNDSCAPES

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1. Where We Are

In the 1990s, Environmental Design and Engineering (EDE) faced a period of declining academic expertise in acoustics and acoustic-related research. This loss of in-house knowledge prompted a shift in the way the Institute approached teaching activities in this field for its Master's programmes. To address the issue, it sought external support, collaborating with both academic institutions, such as London South Bank University, and experienced practitioners. This collaborative effort was instrumental in maintaining the Institute's commitment to delivering high-quality education and research in building and environmental acoustics.

However, a significant turning point occurred in 2018 with the establishment of the Acoustics Group at the UCL Institute for Environmental Design and Engineering (IEDE), under the leadership of Prof. Jian Kang. Prof. Kang's relocation from the School of Architecture at the University of Sheffield to UCL marked an important development for the Institute. With this move, the new Research Theme known as 'Acoustics & Soundscape' emerged. This Research Theme quickly gained momentum with its work on the major EU-funded ERC Advanced Grant project Soundscape Indices (SSID), led by Prof. Kang. As a result, the group began to expand, welcoming its first research staff and PhD students. Over the years, this dedicated group has grown to approximately 15 members, reaffirming UCL IEDE's commitment to pioneering research in this fascinating realm.

The Acoustics and Soundscapes Theme is very much driven by its multidisciplinary approach in investigating how sound propagates in urban areas, buildings and rooms, exploring the human perception and evaluation of various sounds, and engineering methods to control and design soundscapes, as well as supporting the standardisation of soundscape research via the ISO 12913 series. This bridges various scientific disciplines, including architecture, urban planning, environmental science, civil engineering, transport engineering, environmental psychology and social sciences. One key focus of this research group is Urban Soundscapes and Environmental Acoustics. This area examines the acoustics of public spaces, investigating how people perceive outdoor acoustic environments in different contexts, and related frameworks (and obstacles) for standardisation. It also addresses general environmental acoustics and sound propagation outdoors. Researchers investigate social and behavioural aspects related to environmental sounds, such as noise complaints, perceived (auditory) safety and environmental justice, and enhancing our understanding of the impact of urban soundscapes on the human experience, but also other important societal aspects such as soundscape conservation and acoustical heritage.

Another important research trend is noise mapping and soundscape modelling. This explores techniques for measuring, analysing and mapping various sound-related components, whether objective or subjective. It includes the development of prediction models for soundscape perception, leveraging machine learning and neural networks in noise and soundscape studies. By combining scientific methodologies and technological advancements, this research helps shape our understanding of the complex acoustic environments in which we live. Building acoustics, room acoustics and indoor soundscapes form another integral research area within this group. Researchers investigate how sound behaves in confined spaces and semi-public buildings such as offices, museums, transport hubs and hospitals, and how these indoor environments interact with the broader urban context from an acoustic perspective. This research also aims to develop novel theoretical models to redefine acoustic comfort within buildings, making indoor spaces more conducive to wellbeing and productivity.

The UCL IEDE Acoustics Group's research informs its teaching activities within the Institute. Researchers and doctoral students from the group actively contribute to the teaching of IEDE MSc programmes and supervise student dissertations. These dissertations cover a broad spectrum of topics, including relevant contemporary issues such as the effects of the COVID-19 pandemic on urban soundscapes, the connection between sound sources and the mood of individuals in open environments, and the comparison of machine learning algorithms for predictive modelling of the pleasantness and eventfulness of a soundscape. This educational component not only supports the growth of the field but also provides students with the opportunity to engage in meaningful research in acoustics and soundscapes.

2. Research Challenges

Over the next decade, researchers in the area of Acoustics and Soundscapes will face numerous challenges that will require multidisciplinary efforts and significant advancements. One major challenge will be the integration of artificial intelligence (AI) and acoustics. Developing robust AI algorithms that can accurately process and interpret acoustic data in real time across diverse environments is crucial. This involves enhancing AI capabilities for sound identification, separation and synthesis in noisy and reverberant settings, as well as creating high-fidelity acoustic signal processing tools that can operate effectively with limited data under challenging conditions. In the realm of sustainability, leveraging acoustics for environmental monitoring and the development of sustainable technologies will be a concern. Researchers will have to work on utilising sound for large-scale environmental monitoring, biodiversity assessment and climate change mitigation. Additionally, developing sustainable acoustic materials and noise control methods that align with net zero initiatives will be vital.

There is a need for a holistic understanding of soundscapes and their impact on human and ecological wellbeing. This will involve interdisciplinary research to explore the perception of soundscapes in the context of climate change, urbanisation and societal shifts. Biologically inspired acoustic solutions present another exciting frontier. Designing intelligent acoustic devices and systems inspired by biological mechanisms will be a challenging yet rewarding endeavour. Enhanced computational methods for acoustics are essential for the future. Advancing computational models and simulations to better predict and optimise acoustic phenomena will be necessary. This involves pushing the boundaries of exascale computing, machine learning and new mathematical approaches to create more accurate virtual acoustic prototypes and digital twins. Educational and ethical considerations will play a critical role in the development and application of new acoustic technologies. Addressing the educational gap and ethical implications associated with emerging acoustic technologies is crucial. Promoting acoustic education among engineers, designers and the general public, as well as ensuring the ethical use of artificial intelligence (AI) in acoustics, with a focus on diversity, equity and inclusion in the field, will be essential.

Finally, understanding and mitigating the effects of human-generated noise on terrestrial and marine ecosystems will be a pressing challenge. Developing technologies to measure and analyse animal responses to noise, and implementing effective noise abatement strategies to protect wildlife habitats, will be key areas of research. Addressing these research challenges will not only advance the field of acoustics but also contribute to broader societal goals such as public health, environmental sustainability and technological innovation. Through collaborative efforts and interdisciplinary research, the acoustics community can drive significant progress over the next decade.

The Acoustics and Soundscapes Theme has already started tackling some of these challenges in its research projects. These collectively contribute to advancing our understanding of community noise, soundscape perception and its cultural heritage value, the significance of indoor acoustic environments in contemporary living and the standardisation of soundscape assessments across cultures. They address real-world challenges and promote the development of more holistic and inclusive approaches to environmental design and acoustic comfort.

2.1 Soundscape Indices (funded by ERC–Horizon 2020)

A groundbreaking project led by Prof. Jian Kang, Soundscape Indices endeavours to transform the way we approach environmental noise. It addresses the issues faced by 80 million EU citizens affected by excessive noise, emphasising the limitations of conventional sound-level reduction. By introducing the concept of ‘soundscape approach’, this interdisciplinary research seeks to create ‘soundscape indices’ that reflect human comfort levels and redefine the field of built environment acoustics. Key objectives include characterising soundscapes, identifying influential factors, developing indices and demonstrating practical applications in environmental design.

2.2 Influence of soundscapes and lightscapes on cultural heritage perception (funded by UCL Cities Partnership Programme)

This collaborative project with University of Roma Tre explores how soundscapes and lightscapes influence the perception of cultural heritage, with a specific focus on the Colosseum in Rome. The research, a collaboration between UCL, the Polytechnic Institute of Turin and the University of Roma Tre, investigates the interplay between acoustic and lighting environments and their impact on users' experiences. It aims to develop a procedure for evaluating combined acoustic and lighting conditions in artistically significant locations to inform better design and preservation decisions (Flores-Villa et al. 2023).

2.3 Home as a Place of Rest and Work: The Ideal Indoor Soundscape during the COVID-19 Pandemic (funded by CIBSE)

This project examines the significance of acoustic environments in homes during the COVID-19 pandemic, when residences served as places of both work and rest. Researchers in the UK and Italy conduct an online survey to understand how the acoustic environment and building features affect the quality of life and work for individuals. The study seeks to identify ideal indoor soundscapes, consider cross-cultural differences and provide insights into improving home environments for wellbeing beyond the pandemic (Torresin et al. 2019; Torresin et al. 2020).

2.4 Soundscape Attributes Translation Project (funded by UCL Cities Partnership Programme)

The Soundscape Attributes Translation Project (SATP) addresses the challenge of translating international soundscape standards into various languages and cultures. The goal is to make soundscape assessments more inclusive and culturally mindful. By collaborating with researchers from around the world, SATP aims to create validated translations of standardised perceptual attributes for measuring soundscapes. This ensures that the perception of soundscapes is accurately captured in different linguistic and cultural contexts, promoting cross-cultural understanding in the field of acoustic environments (Aletta et al. 2024).

2.5 Deep Learning Techniques for Noise Annoyance Detection Project (funded by UCL Health of the Public)

The Deep Learning Techniques for Noise Annoyance Detection (DeLTA) project addressed the pressing public health issue of environmental noise, which ranks second only to air pollution in Europe. DeLTA aimed to develop a cost-effective deep neural network (DNN) method to detect noise annoyance early in communities and smart cities. The project included four phases: (1) a large-scale online experiment to collect urban soundscape data, (2) DNN development based on the experiment's results, (3) validation in a smart city environment, and (4) exploring noise annoyance's broader implications for public health. DeLTA published its findings, hosted a webinar, and fostered subsequent research and collaborations. This also led to a collaboration with the Alan Turing Institute in the form of a data study group. This interdisciplinary project combined expertise in environmental noise, engineering, statistics, computer science and public health to advance research and address public health and urban planning challenges (Mitchell et al. 2023).

3. Setting the Research Agenda

The UCL IEDE Acoustics and Soundscapes research group is a collaborative hub of multidisciplinary scholars focused on advancing our understanding of sound environments and their profound impact on individuals and communities. Through a diverse array of research activities, the group aims to interpret the complexities of acoustics, noise and soundscape studies while developing innovative solutions to real-world challenges. Its work is underpinned by evidence-based design practices, aiming to create healthier, more sustainable and more inclusive environments for all. The group addresses research topics both in outdoor and indoor environments, as well as how these two 'worlds' interact. This is reflected in the research trends described below, and clustered by these two main domains, accordingly.

3.1 Environmental acoustics and outdoor soundscapes

At the forefront of the group's research efforts is the practical application of soundscape approaches. Recognising the limitations of current assessment methods, the group aims to pioneer methodological advances that facilitate the integration of soundscape engineering into design practices, by also actively engaging in standardisation working group and national and international technical committees (e.g. ISO 12913 series, IEA-EBC Annex 87, etc.) (Mitchell, Aletta & Kang 2022; Mitchell 2022). By shifting from traditional noise control to a more proactive soundscape engineering approach, the group seeks to create tools and frameworks that empower engineers to design environments that prioritise not only noise reduction but also the creation of positive soundscapes conducive to wellbeing and productivity. Developing predictive models that can anticipate human (perceived) soundscapes based on objective and measurable metrics is a key ambition. A critical aspect of the group's research there involves understanding the multifaceted influences on the soundscape, and testing methods for quantitative soundscape data collection, such as soundwalks and large-scale soundscape surveys, to capture the human experience and understanding of everyday acoustic environments both in urban (Figure 1) and natural (Figure 2) contexts. From the psychological wellbeing of individuals to the dynamics of social interactions, the group's scholars explore the interplay between acoustic properties and human-related factors in shaping sound environments. By examining the impact of demographics, social interactions, cultural differences and other variables on perceptions of soundscapes, such research provides insights into how different populations experience and interact with their auditory surroundings (Chen & Kang 2023).

Moreover, the exploration of spatial and temporal variations in soundscapes contributes to a nuanced understanding of the dynamic nature of acoustic environments. In the realm of urban planning, the group's endeavours also extend to investigating the broader implications of sound environments on human health and behaviour. Utilising spatiotemporal analytics and big data mining techniques, the research group explores the relationships between soundscapes and urban landscapes, evaluating the effects of sound environments in cities of various scales, and informing evidence-based urban planning strategies that promote liveable and sustainable urban environments. This will provide urban planners with novel perspectives and tools to integrate soundscape considerations into the fabric of urban design, ultimately fostering healthier and more inclusive cities (Tong & Kang 2020; Tong et al. 2023; Tong & Kang 2021). Quantitative methodologies are not the only approach, and acoustics and soundscape research extend to the qualitative exploration of streetscapes and their auditory dimensions, aiming to comprehensively understand how sound influences perceptions of urban spaces. Focus groups, narrative interviews and other qualitative analyses can offer more insights into the complex relationships between streetscapes and soundscapes, shedding light on the role of sound in shaping urban experiences and quality of life. The group addresses participatory soundscape design, aiming to develop frameworks and strategies that integrate diverse perspectives and enhance public engagement in the design process. By involving communities in the design of their sound environments, the group aims to create inclusive and responsive designs that reflect the needs and preferences of diverse populations. By exploring citizens' perceptions of daily commutes and urban environments, the group's research informs urban design practices that prioritise sensory experiences and foster vibrant and inclusive communities.

Figure 1. Bloomsbury soundscape survey
(Image credit: Dr Tin Oberman)

3.2 Architectural acoustics and indoor soundscapes

Apart from outdoor spaces, the group's research covers buildings and the study of architectural acoustics, looking at the impact of sound environments on human behaviour and experience within indoor built environments. From exhibition spaces to residential settings, the group explores the intricate relationships between architectural design, acoustic properties and human perceptions. By developing models for assessing affective responses to indoor soundscapes, the group's researchers aim to inform evidence-based design practices that prioritise occupant comfort, wellbeing and productivity (Torresin et al. 2020). The goal is not only mitigating the negative effects of noise but also harnessing the potential of sound to enhance human experiences and interactions within built environments. In the context of educational settings, the group's research focuses on creating user-friendly designs for school soundscapes that enhance the wellbeing and learning outcomes of children and the working environments of staff (Cal, Kang & Aletta 2023). By considering the interaction between indoor and outdoor proximity sound sources for school environments, the group develops comprehensive strategies that promote acoustic comfort, minimise distractions and foster positive auditory experiences within educational settings.

Figure 2. Silenzi in Scotland image
(Image credit: Dr Tin Oberman)

Figure 3. Audio lab in G13, UCL Here East Campus
(Image credit: Xiang Fang)

The group integrates environmental domains other than acoustics and, learning from thermal comfort models, its research explores the adjustment of the adaptive acoustic comfort model to indoor soundscapes, investigating how factors such as adaptation, control and expectation influence noise sensitivity and acceptability levels. By examining the adaptation of individuals to sound environments, the group aims to develop frameworks that enhance our understanding of human responses to indoor soundscapes and inform evidence-based design practices that prioritise occupant comfort and wellbeing. Likewise, in confined spaces, the group's research explores innovative approaches to noise mitigation, such as blending soundscape principles with traditional (indoor) barrier designs in open-plan offices and other work environments. Overall, to fulfil such ambitions, the group makes use of the latest technological advancements and the potential of virtual reality (VR) technologies. As shown in Figure 3, the UCL IEDE Acoustics Group's advanced facilities support controlled audio experiments and immersive soundscape simulations. The research delves into strategies for reproducing immersive sound environments with unprecedented realism and effectiveness, investigating rendering and playback methods for VR-based soundscapes. This opens up new possibilities for immersive simulations and applications across various domains, from architectural design to entertainment and beyond (Xu et al. 2021; Xu & Kang 2019).

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UCL IEDE Expert workshop: Reflections and future research pathways

We engaged in discussions about our research challenges and pathways with a group of 23 participants, as listed in Table 1.

Urban sound environments have a significant impact on people's health and wellbeing. This fact is supported by various studies and data from international agencies like the World Health Organization. Traditionally, research has focused on the harmful effects of noise pollution, which include health issues such as cardiovascular diseases, sleep disturbances and mental health problems. These adverse effects are often more severe in lower socioeconomic groups, raising concerns about environmental justice. This inequality indicates that marginalised communities suffer more from environmental noise, calling for fairer urban planning and public health policies. On the other hand, a newer field of study, soundscape studies, views environmental sounds as a resource that can have positive health effects. Good soundscapes, which include both natural and human-made sounds, can make urban life healthier and more sustainable by reducing stress, improving cognitive performance and encouraging social interactions. However, the positive aspects of soundscapes might lead to their commodification, potentially pushing out lower socioeconomic groups and worsening social inequalities. Soundscapes are also linked to natural ecosystems, as human-made sounds can disrupt wildlife and ecological balance. Hence, soundscape quality should be part of broader environmental management that integrates human health and ecological sustainability.

Table 1: Expert workshop participants list

Name	Affiliation
Ruth Bernatek	University of Warwick
Marion Burgess	UNSW
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Gunnar Cerwén	Swedish University of Agricultural Sciences
Marcel Cobussen	Leiden University
Catherine Guastavino	McGill University
Maarten Hornikx	Eindhoven University of Technology
Bhan Lam	Nanyang Technological University
Catherine Lavandier	Université de Cergy-Pontoise
Hui Ma	Tianjin University
Laudan Nooshin	City, University of London
Sarah Payne	University of Surrey
Eleanor Ratcliffe	University of Surrey
Brigitte Schulte-Fortkamp	Technische Universität Berlin
Cynthia Tarlao	McGill University
Simone Torresin	University of Trento

Despite the established scientific knowledge, translating these insights into effective policies has been slow, and there are limited proactive measures to improve soundscape quality within regulatory frameworks. The social and policy dynamics of urban sound environments are complex, involving various stakeholders with differing interests. Previous efforts to address these issues have often failed due to fragmented and isolated approaches. To make meaningful progress, it's crucial to adopt a holistic perspective that considers the complex relationships between soundscape quality and public health. We applied a systems-thinking approach, a first in soundscape studies, to analyse these interactions comprehensively. Systems thinking explores the connections between elements related to a problem, using tools like causal loop diagrams (CLDs) to depict complexity and identify leverage points for intervention and policy development. The systems-thinking approach involves engaging stakeholders to gather diverse perspectives, often through group model-building workshops. These workshops use scripted activities guided by facilitators to develop model mechanisms. Engaging stakeholders in this process can elicit various perspectives, improving the system. Participatory methods are widely used to integrate health into urban planning, housing regeneration and water management. This approach is particularly useful for identifying research gaps and pathways in soundscape quality and public health.

In the workshop, participants focused on feedback mechanisms and intervention points. Feedback mechanisms show how initial changes in the system can cause further changes, often non-linear, across different sectors. Intervention points indicate where to act in a complex system. By exploring the elements contributing to research gaps and their connections, participants formulated comprehensive research pathways. The study employed a qualitative research design using systems thinking to develop a CLD mapping interactions and feedback loops between soundscape quality and public health. Twenty-one experts in urban soundscapes, planning, design, environmental psychology and social sciences participated in the study. These were chosen for their knowledge and experience, ensuring a diverse range of perspectives. Data collection involved two main phases: a pre-workshop mini-CLD and an online workshop. Before the workshop, a subgroup of participants and two CLD experts developed a preliminary list of variables and a mini-CLD. This preliminary model was used for revision and discussion during the workshop, conducted online via Microsoft Teams. The 90-minute session involved structured activities to facilitate the collaborative development of the CLD, including brainstorming key variables and mapping their relationships. Participants identified causal links and their polarity, and the CLD was refined through group discussion.

The final CLD highlighted major feedback loops and their implications for soundscape quality and public health. The discussions revealed four themes, including three reinforcing loops and three balancing loops. These themes illustrated the complex interactions between noise pollution, soundscape quality and socioeconomic dimensions. For instance, the theme of noise pollution and soundscape quality showed that an increase in soundscape quality raises the economic value of a place, which in turn increases community services and noise pollution, forming a balancing loop (B1). The socioeconomic dimension revealed that increased soundscape quality enhances psychological value, which boosts social value and economic value, forming reinforcing loops (R1, R2). However, economic value can also lead to displacement and soundscape gentrification, reducing soundscape quality, forming a balancing loop (B2). Biodiversity and soundscape quality were linked through loops showing that noise pollution reduces biodiversity, which decreases soundscape quality and economic value, but improved soundscape quality enhances biodiversity, forming reinforcing loops (B3, R3).

The CLD highlighted various aspects of soundscape quality and public health, emphasising the interconnected nature of social, psychological and economic values. The study identified several research pathways linked to the CLD, such as epidemiology, soundscape action plans, ecoacoustics and urban studies. These pathways represent strategic areas of research designed to trigger positive impacts throughout the soundscape system.

Future pathways were explored, emphasising ecoacoustics, which focuses on the interactions between soundscapes and ecological systems. This pathway can help mitigate the negative impacts of noise pollution on wildlife and promote the co-benefits of enhanced biodiversity for soundscape quality and public health. Psychoacoustics, which examines the psychological effects of sound, is essential for understanding how soundscape elements influence human perception and responses. Developing prediction models for soundscape perception can help city planners anticipate the impact of different soundscape configurations on public health and wellbeing. This would help mitigate negative impacts like noise pollution and displacement and enhance positive outcomes. Prediction models are part of soundscape action plans that strategically plan and manage urban sound environments. Balancing individual and community needs in soundscape design is crucial. Future research should explore how to design soundscapes that cater to diverse preferences and promote social cohesion. Engaging communities in participatory soundscape planning can ensure that interventions are responsive to local needs and values. Using big data and city-scale research methods can provide comprehensive insights into urban soundscapes and their impacts. Gathering data from sensors, mobile devices and social media can reveal spatial and temporal patterns in sound exposure, identify noise pollution hotspots and evaluate the effectiveness of interventions. This approach can bridge soundscape studies and epidemiological research, providing robust evidence on the links between soundscape quality and public health outcomes. It can also promote environmental justice by advocating for equitable soundscape interventions.

There are of course potential biases to be considered, due to the specific composition of the participant group and the online workshop format. Further validation with additional stakeholders and different workshop formats is recommended. The researchers' diverse academic backgrounds informed their understanding of the issues but may introduce a normative stance prioritising certain values and outcomes.

The systems-thinking approach ultimately revealed the complex interactions between urban soundscape quality and public health through a CLD. The findings emphasise the need for a comprehensive approach that integrates multiple perspectives and disciplines. The systems-thinking approach used in this study makes the mechanisms linking soundscape quality to public health explicit, offering valuable insights for policy makers, urban planners and public health professionals. The CLD serves as a starting point for further research and practice, highlighting the importance of a balanced and holistic approach to ensure equitable and sustainable urban soundscapes.

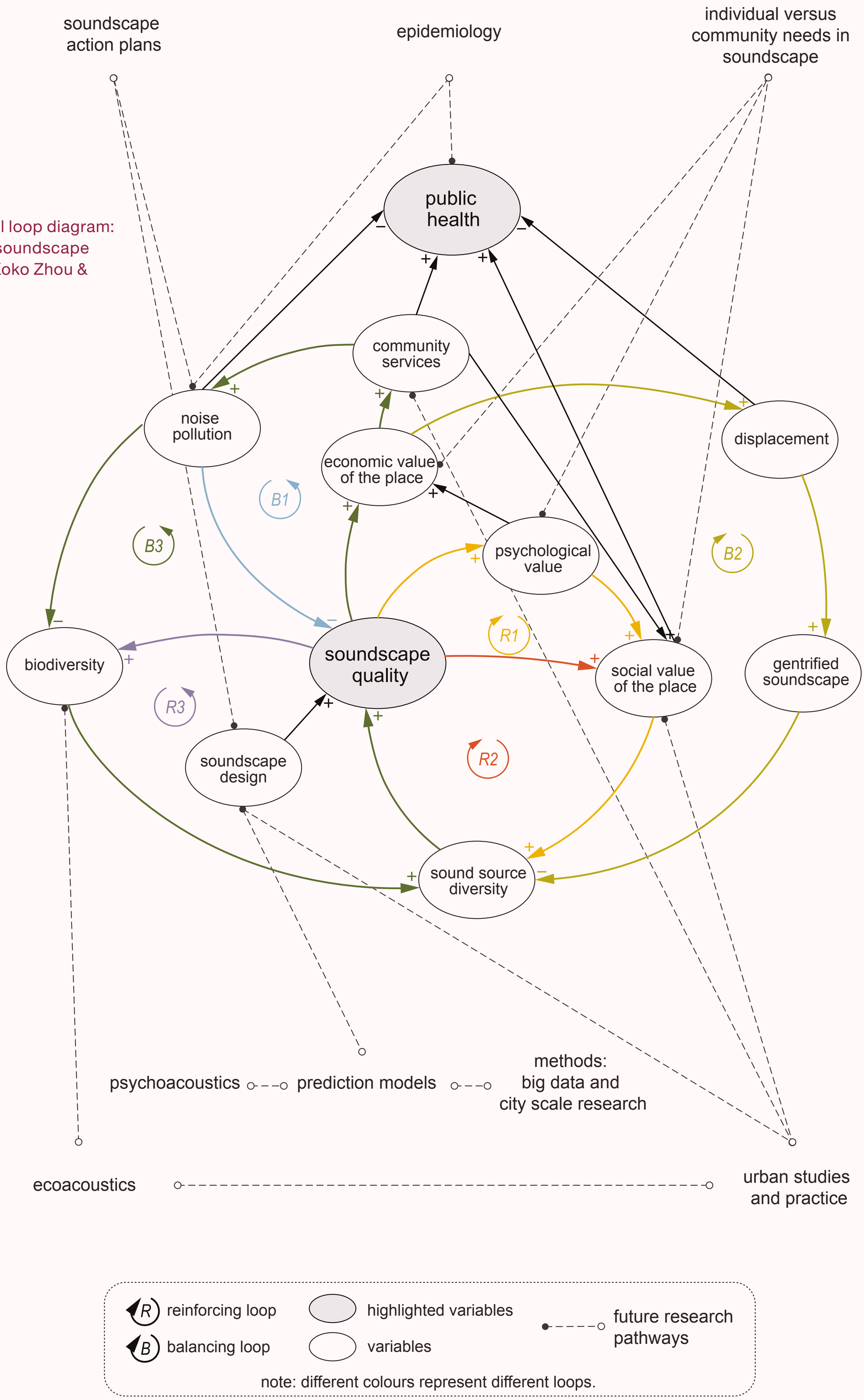

Figure 4. Causal loop diagram: Acoustics and soundscape (Image credit: Koko Zhou & Daijia Ke, 2024)

THEME: MOISTURE, TEMPERATURE AND AIR QUALITY

Contributors: Jiaxu Zhou, Anna Mavrogianni,
Hector Altamirano-Medina

1. Where We Are

Addressing the complex interlinkages between moisture, temperature and air quality in buildings and at the indoor–outdoor continuum has been at the heart of environmental design and engineering research at The Bartlett for the last 60 years. This is a significant part of our efforts to create robust evidence to improve building design, technologies and operation, ultimately improving the environmental quality of buildings and associated health and wellbeing outcomes. Buildings are complex, dynamic, sociotechnical systems seeking to provide solutions to a multitude of sometimes conflicting, often ill-defined design issues; novel engineering tools, systems thinking and transdisciplinary approaches are, therefore, needed to help industry and policy deliver truly sustainable, healthy and equitable built environments, now and in the future, under a changing climate. Our Research Theme experts and researchers are at the forefront of creating integrated multi-environmental factor frameworks for the built environment and providing evidence of how these factors are associated with human health, wellbeing and performance.

1.1 Overview of methodological approaches

We conduct research on hygrothermal and air quality monitoring and testing related to environmental performance. This involves using environmental chambers (Figure 1), conducting extensive national and international field environmental monitoring, carrying out detailed building and social surveys, and implementing interventions in people's homes, schools and workplaces. For example, the UCL Institute for Environmental Design and Engineering (IEDE) led pioneering studies on indoor air quality in UK schools, which raised industry design standards and helped reduce the risk of respiratory and cardiovascular diseases for schoolchildren and teaching staff (European Commission et al. 2014). More recently, in collaboration with Tsinghua University, our Theme members led monitoring-based research that explored conflicts and co-benefits between low-energy and low-carbon building design and indoor air quality, in schools, offices, hospitals and large residential buildings (Stamp et al. 2020). We also have expertise in analysing large-scale government survey and monitoring datasets – for example, to identify dwelling and household characteristics that have significant links with higher indoor temperatures (Petrou et al. 2019). IEDE experts frequently produce industry indoor environmental quality (IEQ) monitoring guidance; for example, several Theme members recently contributed to the Chartered Institution of Building Services Engineers (CIBSE) Technical Memorandum (TM68) Monitoring Indoor Environmental Quality, which aims to provide information to building professionals on the units and instruments used in monitoring thermal comfort, indoor air quality, luminous quality and acoustic quality.

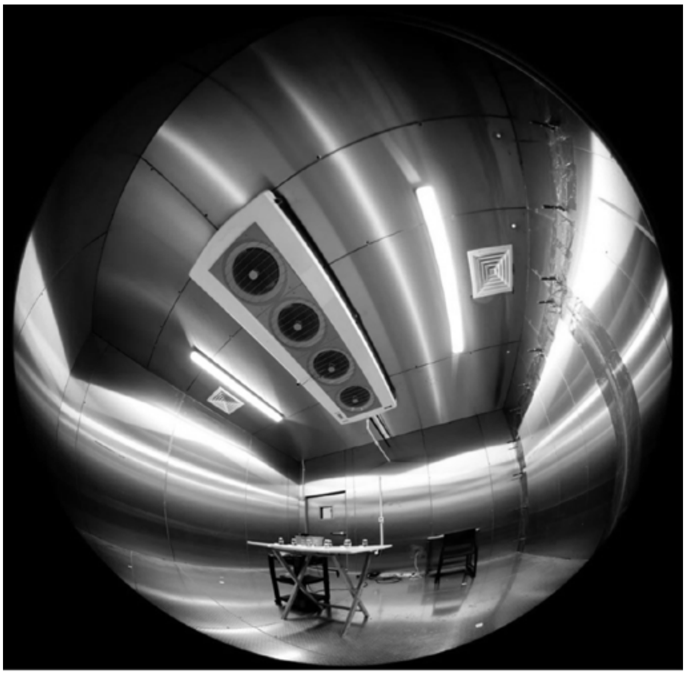

Figure 1. Human environmental chamber at UCL Here East (Image credit: Edward Barrett, 2024)

At IEDE, we are also pioneering the development of powerful, policy-oriented built environment modelling frameworks. Our building stock performance modelling and analysis involves developing a digital model that effectively represents a complex system. These models are used to predict, assess and analyse the dynamic interactions that affect environmental performance, aiding policy makers and supporting decisions in building design and operation. A UK archetype-based housing stock model of indoor environment and energy has been developed (Figure 2), which is able to predict the effect of a wide range of energy retrofit, IEQ improvement and climate scenarios (Symonds et al. 2016). This is a powerful tool that can quantify the relative effectiveness of different policies, retrofit options and behavioural interventions, now and in the future, and associated inequalities, thus informing policy and practice (Taylor et al. 2018; Symonds et al. 2019; Ferguson et al. 2023). UCL IEDE has also developed similar building stock modelling approaches for learning environments – for example, archetype-based (Grassie et al. 2023) and automated one-by-one stock models of the English school building stock (Schwartz et al. 2022). Such frameworks can be linked with other datasets to quantify impacts of different building interventions, such as the impact of indoor air quality on resulting asthma incidence and healthcare costs (Karakas et al. 2023) and cognitive performance (Dong et al. 2023).

Our Theme members also hold influential positions in professional organisations pioneering the adoption of these novel methods in practice and policy. Prof. Dejan Mumovic has made significant contributions to the field, co-founding both the CIBSE School Design Group and the International Building Performance Simulation Association (IBPSA)-England Board, and serving as the Inaugural Chair of the CIBSE Education Guild. Prof. Anna Mavrogianni serves as a member of the CIBSE Knowledge Management Committee and, together with Prof. Rokia Raslan and Prof. Dimitrios Rovas, serves on the IBPSA-England Board. Several Theme members contribute to the activities of the CIBSE Knowledge Generation Panel.

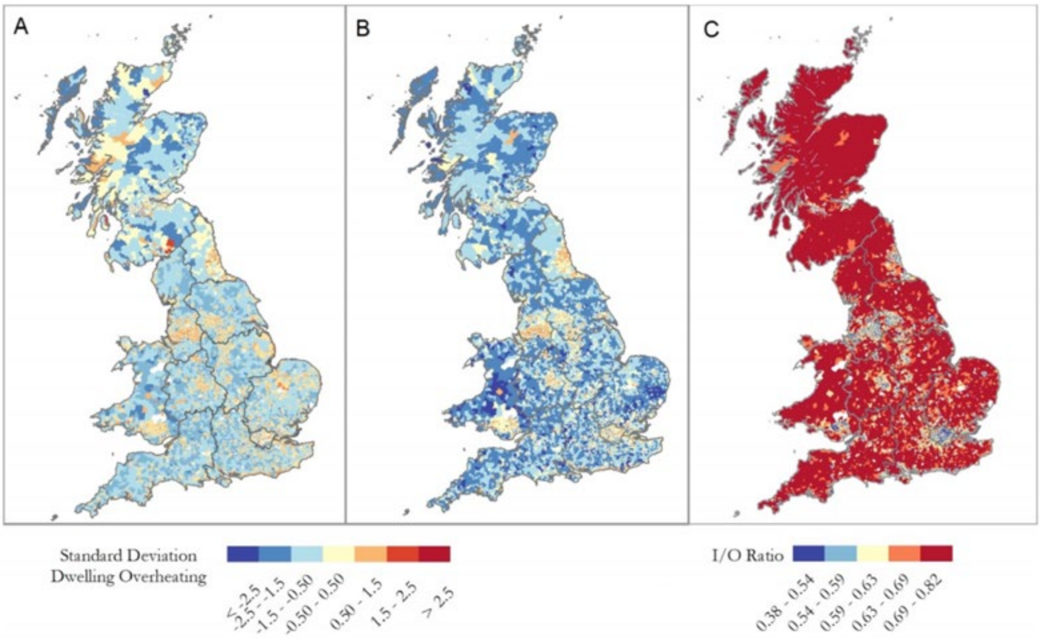

Figure 2. Housing stock modelling outputs: (A) Mean maximum daytime living room temperature (oC), (B) Mean maximum nighttime bedroom temperature (oC), (C) Indoor/Outdoor ratios for PM2.5 (Image credits: Taylor et al. 2016)

1.2 Climate change and heat–health resilience research

Our team is internationally excellent in generating innovative research in the climate change adaptation of buildings and cities in the context of net zero, health and wellbeing. For example, we led the first large-scale study on the climate resilience of care settings in the UK, using both monitoring and modelling methods. The study produced novel evidence on the health benefits of building adaptations to protect care home residents against heat in the context of uncertainty over loss of life expectancy from heat exposure (Ibbetson et al. 2021). At the urban scale, UCL IEDE research has quantified the extent to which cooling brought by trees could lower heat-related mortality in cities such as London (Taylor et al. 2024), and how additional moisture in the atmosphere may increase human heat stress (Simpson et al. 2023). We have closely collaborated with government, policy makers and industry in this area. Prof. Mike Davies is a member of the UK Climate Change Committee and the Adaptation Committee. Several Theme members co-authored chapters in the 2023 UK Health Security Agency Health Effects of Climate Change report, and contributed to the UK Climate Change Risk Assessment (CCRA3). We are currently contributing to the upcoming CCRA4, with Prof. Dejan Mumovic, Dr Valentina Marincioni, Bingyu Xu and Dr Jiaxu Zhou actively leading the working groups for Facilities Delivering Public Services, Resilience of Buildings and Communities, and Indoor Environmental Quality.

1.3 Indoor air quality research

We combine monitoring, modelling and empirical evidence-based experiments to assess risks associated with indoor air quality. Compensatory ventilation filtration and occupant behaviour can be studied to help mitigate poor indoor air quality in buildings. In our recent research, we address the complexities of indoor air quality and pollution, including pollutants such as particulate matter, carbon monoxide, radon and volatile organic compounds, and their impact on human health wellbeing and performance. For instance, we integrate theories and approaches from psychology, psychiatry and medicine to understand how human cognitive performance is associated with indoor air quality (Chen et al. 2023) and air pollution (Zhou et al. 2023, 2024) in lab and real-world office settings, as well as evaluating the combined impact of ventilation and thermal conditions on cognitive performance in higher education settings (Ahmed et al. 2022). Our research also identifies and tests effective interventions for improving indoor air quality which enhance occupants' satisfaction (Cooper et al. 2021), productivity (Zhou et al. 2022) and health (Cooper et al. 2022), as well as reducing health inequalities (Ferguson et al. 2020). Furthermore, we have carried out projects to evaluate the impact of air cleaning in nurseries during the COVID-19 pandemic (Zhang et al. 2023) and contributed to a handbook on indoor air quality with a chapter on daycare centres (Zhang et al. 2022). Our research underpinned by the building stock modelling mentioned earlier includes the quantification of the impact building energy efficiency measures have on the concentration of radon in dwellings (Symonds et al. 2019) and traffic-related pollutants in schools (Grassie et al. 2023), and the associated effects on occupant health (Karakas et al. 2023) and cognitive performance (Dong et al. 2023). On a global scale, we have estimated the population-weighted exposure to household air pollution for fine particulate matter and its attributable health burden (Mohajeri et al. 2023a, 2023b).

We have actively engaged with governmental bodies, policy makers and industry representatives to contribute expertise in various capacities. For instance, Prof. Sani Dimitroulopoulou and Prof. Marcella Ucci act as the Chair and Vice-Chair, respectively, of the UK Indoor Environments Group. Prof. Ucci also co-leads CIBSE's Health and Wellbeing Working Group, and was recently invited to provide oral evidence at All-Party Parliamentary Groups enquiries on Healthy Homes and Buildings, and Design and Innovation, and contributed to the Working Group of the Royal College of Paediatrics and Child Health on Indoor Air Quality and Children's Health (Holgate et al. 2020).

1.4 Moisture research and the UKCMB

Moisture research at IEDE has focused on tackling the significant uncertainties in methodologies and a notable absence of fundamental data and research. Although our work around moisture began in the early 2000s, with work around new insulation materials, mould growth and revision of standards, among others, it was not until 2017 that these efforts were consolidated. This consolidation marked the establishment of the UK Centre for Moisture in Buildings (UKCMB). The UKCMB's mission is to advance understanding of the causes, mechanisms and solutions related to moisture issues in buildings. Bringing together research and initiatives from academics and PhD students, the UKCMB has provided independent, authoritative research, education, guidance, training, innovation and policy engagement on a global scale.

Since its establishment, the UKCMB has supported industry and government through research initiatives on moisture analysis and damp prevention in social housing, enhancing energy efficiency and improving living conditions. Our research has focused on improving the health of occupants and the durability of the building fabric, ensuring long-lasting and healthier homes. For example, we have developed and assessed novel insulation systems and advanced solutions for retrofit and new-build construction. We also engage national and international experts in a collaborative approach, ensuring that our work remains at the forefront of addressing building moisture-related challenges, advancing both academic and practical solutions. In 2021, we launched the first International Conference on Moisture in Buildings (ICMB), solely focusing on moisture-related topics (Figure 3). The 2021 and 2023 conferences covered topics such as monitoring and modelling moisture, ventilation, airtightness, moisture in existing buildings and retrofits, materials performance, building decay, indoor mould growth, moisture in historic/traditional buildings, and the impact of moisture on health and wellbeing, as well as climate-induced moisture issues.

Figure 3. Human environmental chamber at UCL Here East (Image credit: Edward Barrett, 2024)

We have actively engaged with policy makers and the public to shape policies and promote behaviour change surrounding damp and mould in buildings. Our contributions include the British Standards Institution (BSI) white paper on the importance of standards for energy retrofit, BS 40101 on Building Performance, UK Government guidance on health risks of damp and mould, BS 5250:2021 Management of Moisture in Buildings, PAS 2030, 2035 and 2038, and involvement in the BSI Retrofit Standards Task Group, among others. In addition, UKCMB has developed various free, accessible resources for homeowners to understand and manage mould and damp in their homes, designed to educate and assist housing providers, councils and homeowners in effectively managing moisture-related issues. We have also created and delivered continuous professional development courses, webinars and talks on tackling mould and damp, sharing our knowledge and expertise with the community.

2. Research Challenges

According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment (AR6) Working Group (WG2) report, there is very high confidence that anthropogenic climate change, reaching 1.5°C in the near term, will increase multiple climate hazards, with catastrophic effects for human health globally (IPCC 2022). The projected rise in ambient temperatures, the frequency, magnitude and severity of heatwaves, and their potential adverse effects for human comfort and health are an increasing concern for the UK (Royal Society 2021; Betts & Brown 2021). Several of the UK's record maximum monthly temperatures have been documented in the last decade, with summer temperature extremes (95th percentile) warming much faster than the summer mean (Kennedy-Asser, Andrews & Mitchell 2021), highlighting the need to quantify the impact of changes in both outdoor temperature variability and extremes on building indoor thermal performance. An increased probability of warmer, wetter winters and hotter, drier summers is projected for the UK, alongside an increase in the frequency and intensity of extremes. Exceptionally hot weather has been experienced in recent years; in the summer of 2022, an unprecedented 40°C heatwave caused more than 3,200 excess deaths in England and Wales (ONS 2022a). Buildings in the UK and similar climates have not been designed with warmer weather in mind, and significant changes are required in the retrofit of existing buildings and design of new buildings to future-proof their performance and occupant thermal comfort and wellbeing as outdoor temperatures increase. However, the UK will remain a heating-dominated climate for decades to come. Cold weather poses significant health risks to the UK population currently and will continue to do so in the near- to mid-term future, with older and lower-income populations being disproportionately affected. For example, a prolonged low-temperature spell occurred in 2022, with the leading cause of excess death being influenza or pneumonia (ONS 2022b). Older people and those suffering from poor health, in particular those living with cardiovascular, respiratory and neuropsychiatric conditions, are most at risk from excess heat and cold, damp conditions and air pollution (Arbuthnott & Hajat 2017). There is also mounting evidence on the impacts of temperature on mental health, but more research is needed in this area (IPCC 2022; Thompson et al. 2018). In the meantime, there has been renewed interest in the adverse health effects of damp conditions, mould and poor air quality, in particular for child and adolescent health and social housing in the UK (Awaab Ishak and the politics of mould in the UK 2022; Renshaw et al. 2022). It is recognised that systemic, underlying socioeconomic inequalities and inequities, and social isolation, can magnify the negative effects of environmental exposures in a changing climate (Munro, Boyce & Marmot 2020; Paavola 2017; Ferguson et al. 2021).

In epidemiological literature, the population-level relationship between outdoor temperature and heat-and cold-related mortality and morbidity is well established (Gasparrini et al. 2015). There are, however, significant knowledge gaps and increasing complexities concerning less-studied determinants of temperature-dependent health outcomes and inequalities, including synergies with moisture and air pollution indoors and outdoors, for different population groups and individuals with complex needs. The severity of environmental risks and adverse health outcomes greatly depends on intersecting exposure, vulnerability, inequity and near-term climate change mitigation and adaptation actions. Temperature-related health risks are also exacerbated by the urban heat island (UHI) effect in cities (Heaviside 2020).

Regional and urban climate and building model simulations are available at increasingly higher spatiotemporal resolutions. Quantifying, understanding and accounting for modelling uncertainties and their propagation across different scales and modelling platforms is, nevertheless, a research priority. This is necessary in order to provide robust estimates of future building performance and appropriate evidence-based recommendations for policy and practice. In addition, capturing temperature spatiotemporal variations, due to the UHI effect, now and in future, is vital for environmental health risk assessment (Heaviside, Vardoulakis & Cai 2016). Crucially, moisture, temperature and air quality exposures occur not only outdoors when travelling and during leisure activities but also at home and in workplaces and schools – that is, across the outdoor–indoor continuum: it is estimated that people in the UK spend on average 90% of their time indoors, and this percentage is likely to be higher for vulnerable individuals. The indoor environment is a key modifier of the environmental exposures and their resulting impacts on health. Past work has shown, for example, that dwelling characteristics cause larger temperature exposure variations than the UHI (Taylor et al. 2015). In addition, while understanding moisture movement and risk in buildings has improved, significant knowledge gaps remain in relation to a changing climate. Research has expanded to include various building types and retrofits, highlighting moisture's impact on both occupant health and building integrity (Marincioni et al. 2021). Inappropriate moisture levels in buildings are a common cause of structural failures and occupant health problems, but despite increased awareness and revised standards, the industry still faces substantial uncertainties and needs further research.

Combined with the climate change adaptation challenges outlined above, challenges emerge in relation to climate change mitigation actions. Building stocks will undergo unprecedented transformations in the context of the net zero transition, aiming to increase energy efficiency, decrease winter fuel poverty and address cost-of-living crises. This is crucial for moisture balance, temperature and air pollutant distributions, because the required increases in building fabric thermal insulation and air tightness will diminish existing air exchange paths that previously relied on unintended infiltration (Petrou et al. 2022). Net zero measures could, therefore, have unintended consequences relating to moisture, temperature and air quality, when not accompanied by appropriate improvements in purpose-provided ventilation (Taylor et al. 2023) or the introduction of building system upgrades, such as heat pumps that provide cooling as well as heating. Vulnerable groups and households with limited adaptive capacity to improve their environments will be hit worst by such cases of maladaptation, further intensified by fuel poverty, overcrowding and changing building uses, thus widening health inequalities.

To conclude, the research problems facing the moisture, temperature and air quality field are complex and not fully understood, with many uncertainties regarding their extent, effects and causes. We need empirical data collection processes and tools co-designed with stakeholders to quantify the indoor modification effect on exposures and understand moisture, temperature, air pollution and health relationships, in the context of net zero and a warming climate. Ultimately, there is a need to target interventions at vulnerable populations instead of using a one-size-fits-all approach.

3. Setting the Research Agenda

Looking forward, our research agenda for the next decade at the IEDE Research Theme on Moisture, Temperature and Air Quality will build upon our established foundations, and expand into critical areas to address the complexities of moisture, temperature and air quality management in buildings and cities. Discussions during three collaborative internal workshops and two workshops with external international experts in 2024 (see Box 1 for details) have helped us shape the research agenda for our Theme to respond to the research challenges outlined above.

A core emergent theme is the assessment of wellbeing and health impacts and inequalities of environmental exposures, including moisture, temperature and air quality, across the outdoor–indoor continuum for vulnerable populations, now and in the future at policy-relevant global warming levels. This is underpinned by:

1. novel climate-building-health data integration;
2. advanced hygrothermal and air quality monitoring underpinned by our state-of-the-art environmental chambers and field measurement equipment, in conjunction with occupant surveys; and
3. active stakeholder engagement to co-design targeted and equitable adaptation solutions for vulnerable populations, to reduce adverse health and wellbeing effects and inequalities.

Specific research agenda items include:

Advancement of risk characterisation techniques to better understand moisture, temperature and air quality interactions

Standardised methodologies for mould growth, thermal discomfort and air pollution assessment and diagnostics

Using the advanced techniques described above, quantification of the spatiotemporal variation of indoor–outdoor moisture, temperature and air quality, and related variables and their extremes, as well as optimisation of ventilation strategies for effective moisture, temperature and air pollutant control

Characterisation of metrics and associated uncertainties, linked to health and wellbeing outcomes for present-day and policy-relevant warming levels, with a focus on less-studied environmental health effects – for example, the impact of specific pollutants, impacts on mental health, or impacts for people living with neuropsychiatric conditions

Mapping of the spatiotemporal variation of health inequalities associated with variability in indoor–outdoor exposures, and including UHI effects, for different socioeconomic groups with a focus on vulnerable populations and different levels of adaptive capacity

Integration of advances in artificial intelligence (AI), in particular machine learning, and Digital Twin technologies in indoor environment modelling and monitoring

Application of systems-based approaches to create transformative change pathways and develop stakeholder co-designed targeted solutions that combine climate change adaptation and mitigation strategies at urban and building levels, in the context of urban transformations and net zero targets, ensuring our findings are readily applicable in the public domain

Crucially, consolidation of our collaboration with other IEDE Themes and groups integrating light and acoustics considerations into our mould, thermal discomfort and air pollution prevention strategies

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Expert workshops: Reflections and future research pathways

The Research Theme Expert Workshops on Moisture, Temperature and Air Quality explored the interconnections between these environmental factors and their impact on health, wellbeing and health inequalities. The workshops were led by Anna Mavrogianni, Hector Altamirano-Medina and Jiaxu Zhou, and facilitated by Rebecca Kemp, an independent moderator, and Yuhong Wang, systems dynamics expert. Both workshops took place online on 7 May 2024, one in the morning and one in the afternoon. Each session featured presentations from the Research Theme leads and extensive discussions among a diverse group of world-leading experts representing a diverse range of institutions and disciplines internationally (Table 1). The agenda was structured around four main parts: Welcome and introductions, Presentation, Discussion and Closing remarks. IEDE's mission and vision were shared with the experts, who subsequently shared their own perspectives and identified research priorities.

On behalf of the Research Theme, Anna Mavrogianni presented an overview of UCL IEDE's research in environmental design and engineering, highlighting key projects and important developments on moisture, temperature and air quality research in recent years, as well as plans to celebrate the 60th anniversary of environmental design and engineering at UCL. The organising team then introduced an initial working causal loop diagram (CLD), developed following three internal Theme workshops. During the workshops, the CLD was used as a tool to visualise and understand the complex interactions between moisture, temperature and air quality, health, and health inequalities. It also enabled the visualisation of research gaps and potential future research pathways by linking various elements, such as outdoor and indoor moisture, temperature and air quality parameters, with human health and health inequalities-related variables. Figure 4 illustrates the CLD following updates informed by the workshop discussions, where a reinforcing loop (R) is a feedback loop in a system that indicates an action is amplifying or reinforcing itself over time, leading to either exponential growth or decline; and a balancing loop (B) is a feedback loop in a system that works to maintain stability by counteracting change.

Table 1: Expert workshop participants list

Name	Affiliation
Fabrizio Ascione	University of Napoli Federico II, Italy
Shijie Cao	Southeast University, China
Nicola Carslaw	University of York, UK
Anne Marie Eijkelenboom	Delft University of Technology, Netherlands
Nesreen K. Ghaddar	American University of Beirut, Lebanon
Colin King	SERO, UK
Roberto Lamberts	Federal University of Santa Catarina, Brazil
Joseph Little	TU Dublin, Ireland
Li Lan	Shanghai Jiao Tong University, China
Lidia Morawska	Queensland University of Technology, Australia
Horace Mui Kwok Wai	Hong Kong Polytechnic University, HK-China
Zaheer Nasar	Cranfield University, UK
Catherine Noakes	University of Leeds, UK
Fergus Nicol	London Metropolitan University, UK
Vahid Nik	Lund University, Sweden
Anna Laura Pisello	University of Perugia, Italy
Priya Rajagopalan	Royal Melbourne Institute of Technology, Australia
Rajan Rawal	Centre for Environmental Planning and Technology, India
Staf Roels	KU Leuven, Belgium
Stefano Schiavon	University of California Berkeley, USA
Tim Sharpe	University of Strathclyde, UK
Pawel Wargocki	Technical University of Denmark, Denmark
Anne Mette Madsen	National Research Center for the Working Environment, Denmark

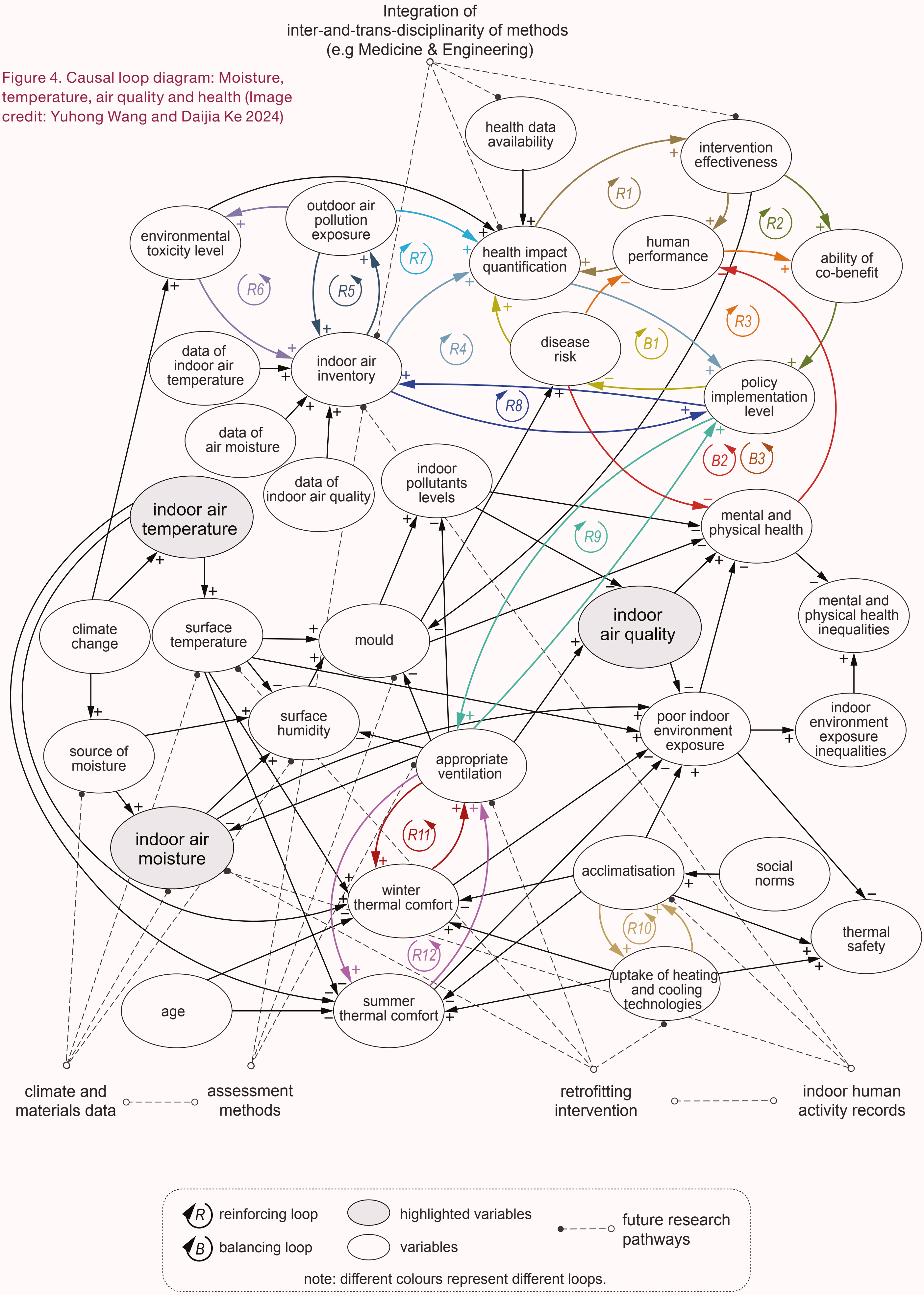
The workshop delved into the intricate relationships between moisture, temperature and air quality, and their individual and synergistic effects on wellbeing, health and health inequalities. The invited international experts contributed diverse perspectives from their fields, highlighting the complexity and interdependencies of these factors, but also the need to consider synergies and conflicts with additional environmental aspects, such as acoustics and lighting. A consensus emerged on the necessity of adopting a broader range of acceptable conditions rather than static, single-factor optimal environment design and operation criteria. This inclusive approach recognises physiological, cultural and geographical differences among individuals and populations to promote greater environmental comfort (e.g. loops R11, R12) and health (e.g. loops B1, B3 and R1).

The discussion also emphasised the significant challenges posed by climate change, alongside increased health inequalities and energy poverty. There was an urgent call to address these issues through sustainable building practices and policies (loop R9) that both mitigate and adapt to climate change, while recognising systemic inequities and capacities, and diverse levels of adaptive capacity among vulnerable populations (loop R10). Experts underscored the importance of retrofit strategies that improve both building energy efficiency and IEQ; ensuring a healthy indoor environment was considered to be as crucial as achieving energy efficiency. Opportunities for research advances in this area were identified through: (i) linking health and environmental research data, and (ii) advocating for inter- and trans-disciplinary research, with the ultimate aim of (iii) developing comprehensive strategies for enhancing IEQ, health and wellbeing. The workshop highlighted the need to consider both physical and mental health and wellbeing when evaluating IEQ (loop B2), as novel evidence in this area is emerging, including data on the impacts of IEQ on cognitive performance, sleep quality, quality of life etc. In addition, there was a strong emphasis on the need for effective policies and public awareness campaigns to promote healthier indoor environments (loop R4). Educating the public about the health impacts of IEQ and encouraging behaviour changes to improve indoor environments were considered crucial. Workshop participants also acknowledged existing data gaps and the challenges in conducting comprehensive research on IEQ. Better and broader data collection methods and the effective integration of existing datasets is encouraged to provide a more complete understanding of the health effects of indoor environments.

In identifying future research priorities, experts stressed the need to explore sustainable and energy-efficient alternatives to traditional heating and cooling methods. Developing and implementing affordable and portable sensors to measure indoor air and other environmental parameters should be a priority. This could provide real-time data on IEQ, addressing risks associated with exposure to excess moisture, heat/cold and air pollutants more effectively. The health impacts of poor ventilation and environmental quality in buildings, particularly in underprivileged areas, were emphasised, with calls for more research to quantify these impacts and develop interventions to improve IEQ.

In summary, the Research Theme Expert Workshops on Moisture, Temperature and Air Quality were highly productive and collaborative events. The discussions accentuated the complex interplay between indoor environmental factors and health, thus highlighting the need for holistic approaches and systems thinking to empower research and policy development. The experts identified critical research priorities, including the need for low-cost sensors, the importance of addressing and monitoring air quality and environmental factors in buildings, and the potential development of sustainable strategies; and research efforts on physical and mental health, wellbeing and productivity. The significance of inter- and trans-disciplinary research and the necessity of combining health and environmental data to develop effective interventions are highlighted. Ongoing collaboration and public engagement to address the pressing challenges of poor IEQ, health inequalities and climate change are urgently needed for the success of global efforts to advance human and planetary health.

Figure 4. Causal loop diagram: Moisture, temperature, air quality and health (Image credit: Yuhong Wang and Daijia Ke 2024)



THEME: CLIMATE CHANGE, SUSTAINABILITY AND CITIES

Contributors: Clare Heaviside, Charles H. Simpson, Oscar Brousse, Koko Zhou, Giorgos Petrou, Irene Pluchinotta, Michael Davies, Dashamir Marini, Yuhong Wang

1. Where We Are

Climate change is a matter of increasing public concern. Climate mitigation and adaptation are major strategic priorities in the UK; the UK is committed to net zero greenhouse gas (GHG) emissions by 2050 and was one of the first countries to legally commit to responding to climate change – through the 2008 Climate Change Act (UK Government 2008). UCL Institute for Environmental Design and Engineering (IEDE) contributes cutting-edge research which helps shape the UK National Climate Change Risk Assessment (Climate Change Committee 2021; DEFRA 2022) and National Adaptation Programme (DEFRA 2024), which are published every five years, providing support for policy at local, national and international levels.

Buildings contribute about one-third of the UK's GHG emissions (Climate Change Committee 2015) and 21% globally (Cabeza et al. 2022), so are a key context for decarbonisation. People in the UK spend most of their time indoors, making buildings a key moderator of their exposure to environmental hazards. Furthermore, 80% of the UK population live in urban areas, which pose health challenges due to heat, air pollution and the concentration of poor-quality housing; together, these may contribute to social inequity of health outcomes (Marmot et al. 2010). Climate change is projected to increase heatwaves and rain intensity in the UK, so will exacerbate problems of heat and flooding, which are a risk in urban areas. IEDE has researched the topics of climate change, sustainability and cities for decades, from both mitigation and adaptation angles. Much of our work at IEDE is concerned with tackling the mitigation of GHG emissions together with adaptation (reducing the impact of climate change) to ensure healthier, more resilient and more sustainable cities.

Our research on climate change, sustainability and cities feeds into several of our higher education programmes. In particular, critical perspectives and research on how to tackle climate change and its impacts within urban environments are taught in both our MSc programmes: Environmental Design and Engineering (https://www.ucl.ac.uk/prospective-students/graduate/taught-degrees/built-environment-environmental-design-and-engineering-msc), and Health, Wellbeing and Sustainable Buildings (https://www.ucl.ac.uk/prospective-students/graduate/taught-degrees/health-wellbeing-and-sustainable-buildings-msc). Our newly designed BSc/MEng programme, named Sustainable Built Environments, Energy and Resources (https://www.ucl.ac.uk/bartlett/environment-energy-resources/study/sustainable-built-environments-energy-and-resources-bsc-and-meng), also directly builds upon our research expertise.

In this chapter we focus on adaptation to the changing climate, and especially to the increasing hazard posed by extreme heat, as well as broader challenges around urban health. Due to the complexity of challenges posed by climate change, our department has various strands of work: topics in this Theme overlap with those discussed in other chapters. More information about work at IEDE on GHG emissions mitigation can be found in the Chapter 1.8 of this book, and more information about issues of indoor environmental quality in Chapter 1.4. See Chapter 1.9 for a more holistic and sociotechnical perspective of the issue. This section highlights some recent relevant research projects at IEDE.

1.2 Urban water

The UK's third National Climate Change Risk Assessments (CCRA3) identified flooding and water resources as priority areas for the UK. IEDE's research has addressed this from social, engineering and sustainability angles through systems approaches in an urban context.

CAMELLIA (Community Water Management for a Liveable London) (https://www.camelliawater.org/) is a research project funded by the Natural Environment Research Council (NERC) (2018–2024) that brings together experts in environmental science, engineering, urban planning and socioeconomics with governmental and planning authorities, industry, developers and citizens to co-develop solutions for sustainable water and environmental management to support housing growth in London. The project focuses on building strategic partnerships with stakeholders, understanding communal perceptions of water management, integrating models to represent the urban water cycle and developing tools to facilitate informed decision-making. A systems-thinking approach and water management tools were developed through case studies in urban renewal, housing development, water infrastructure regeneration and flood risk management.

VENTURA (Virtual Decision Rooms for Water Neutral Urban Planning) (2021–2024) (https://www.ucl.ac.uk/bartlett/environmental-design/research-projects/2024/apr/virtual-decision-rooms-water-neutral-urban-planning-ventura) was a project funded by the Engineering and Physical Sciences Research Council (EPSRC) with the aim of supporting water neutrality decisions through digital tools, bringing expertise from UCL, Imperial College and the British Geological Survey. The UCL team led the participatory systems-thinking activities in case studies in Greater Manchester and Enfield, London.

1.3 Public health and climate policy

Much of IEDE's research aims to improve public health from an environmental perspective. Public health outcomes and policy considerations are a key focus for much of our research. The 2022 Research Excellence Framework Impact Case Study stated:

"Bartlett research has been pivotal in shaping the UK government's position that risks to health, wellbeing and productivity from overheating in homes is an important climate-change risk facing the country. This has led to new policy and new recommendations for building regulations to address the risk of overheating in homes." (https://www.ucl.ac.uk/impact/case-studies/2022/apr/tackling-climate-and-health-risks-overheating-buildings)

CCRAs (National Climate Change Risk Assessments) (https://www.ukclimaterisk.org/newsroom/ccc-to-advise-the-government-on-its-fourth-assessment-of-uk-climate-change-risks/) provide a recurring assessment of risks to the UK in relation to climate change, across all sectors, including health and the built environment. IEDE has contributed to multiple CCRA assessments and is leading the 'Built Environment and Communities' technical report chapter for publication in 2025. Systems analysis and engagement by researchers at IEDE was a key factor in highlighting building overheating as the second most important climate risk facing the UK in the 2nd CCRA (https://www.ucl.ac.uk/impact/case-studies/2022/apr/tackling-climate-and-health-risks-overheating-buildings). This led to the inclusion of building overheating in the 2018 National Adaptation Plan, meaning that it was being addressed by policy. IEDE researchers contributed to government-commissioned research into overheating in new homes. This all eventually led to the creation of overheating standards for new homes through the Future Homes Standard and Part O of the Building Regulations, and is a clear example of the impact of research on policy.

IEDE members contributed to The Lancet Countdown (Household Air Pollution Indicator led by Dr Nahid Mohajeri), which aims to monitor the health aspects of climate change through an annual assessment produced by an independent international collaboration (https://www.thelancet.com/countdown-health-climate). This includes annual tracking of the estimated impacts of climate change on health, as well as tracking of delivery of commitments made by governments.

CUSSH (Complex Urban Systems for Sustainability and Health) (https://www.ucl.ac.uk/complex-urban-systems/) was a Wellcome Trust funded project (2018–2024) to deliver global research on the systems that connect urban development with population health. Across six cities (London, UK; Rennes, France; Kisumu and Nairobi, Kenya; Beijing and Ningbo, China) and with partner organisations on four continents, pathways were developed to improve population health and sustainability through participatory systems-thinking modelling processes. CUSSH enabled community participation in urban planning and environmental management in Kisumu, supported sustainable spatial plans in Kenyan cities with evidence-based tools, and built policy-maker capacity for systems thinking in Rennes and London. Evidence from Kisumu and Homa Bay in Kenya supported the integration of health and sustainability evidence in informing urban infrastructure investments, which influenced regional and national policies.

ClimaCare (2019) (https://www.ucl.ac.uk/bartlett/environmental-design/research-projects/2023/nov/climacare-climate-resilience-care-settings) was a NERC-funded project through the UK Climate Resilience Programme to investigate solutions to overheating in care homes in the UK. It is especially important to adapt the care sector to increasing temperatures, due to the health sensitivity of care users. The project used monitoring and modelling of the thermal environment of multiple UK care homes to evaluate the costs and benefits of adapting care home buildings in the face of increasing summer temperatures. Alongside collaborators including the Department of Health and Social Care, ClimaCare is helping to inform policy around care provision.

HPRU (Health Protection Research Units) on Environmental Change and Health (https://www.lshtm.ac.uk/research/centres-projects-groups/hpru-ech) are National Institute for Health and Care Research (NIHR)-funded projects to address health protection in priority areas in collaboration with universities and the UK Health Security Agency (UKHSA). UCL was partner for all three HPRUs in Environmental Change and Health, starting in 2014. Specific work packages focused on healthy, sustainable cities and urban environments, both indoor and outdoor.

PAICE (Policy and Implementation for Climate & Health Equity) (https://www.ucl.ac.uk/bartlett/environmental-design/research-projects/2024/dec/policy-and-implementation-climate-health-equity-paice) is a Wellcome-funded research collaboration between UCL, LSHTM, the UK Climate Change Committee (CCC) and the Greater London Authority (2023), to inform and evaluate policies that contribute to the transformation of the UK towards a healthy net zero future with a transdisciplinary approach. Using a systems-thinking approach, the co-benefits and unintended consequences of policies will be analysed across the building, energy, transport and food sectors. Indicators of progress will be co-produced to inform the CCC's climate change adaptation and mitigation monitoring frameworks, drawing on the research team's competencies in health impact assessment, building and energy modelling.

IEDE is currently leading two projects under Climate Solutions for a Net-Zero World (CS-N0W) (https://www.gov.uk/government/publications/climate-services-for-a-net-zero-resilient-world/cs-n0w-overview). In these projects IEDE researchers are working in collaboration with the Department for Energy Security and Net Zero (DESNZ), Greater Manchester Combined Authority and The University of Manchester. The first project is assessing the heat vulnerability of residents in Manchester under a warming climate and home retrofit. The second project is developing a health impact model within DESNZ's National Building Model. This model can consider the health impacts and associated healthcare costs of home energy efficiency policy.

2. Research Challenges

The following decades will require electrification to decarbonise building heating, which will need a large programme of building retrofit to be achieved; but this is also an opportunity to improve indoor environmental quality, adapt buildings to future extreme heatwaves, and address inequalities such as energy poverty and exposure to heat (see chapters 1.4 and 1.8). Making the case for integrated mitigation and adaptation strategies will require improvements in methods and data for health impact assessment, better measurement of indoor environments, and more accuracy in exposure estimates and exposure-response functions. It will require expansion of modelling to a greater variety of realistic scenarios, and integration of modelling across scales (e.g. building scale, neighbourhood scale and city scale), all of which must be accompanied by the acquisition of new urban observations (Figure 1) that will be required to properly understand and validate these models.

Large-scale adaptation to climate change, especially the effects of heatwaves, can be addressed through changes to the built environment, especially through changes such as cool roofs (changes to roof albedo) and urban greening. These can change the heat flux of the urban environment and therefore mitigate the health effects of extreme heat. There may be a strong strategic case for such interventions justified by health and economic impacts, but such changes have mainly been trialled at small scales, and the effects that would be achieved at large scales remain uncertain. Modelling is therefore necessary to establish the business and strategic case for large-scale application. A collaborative workshop with external international experts in 2024 (see Box 1) emphasised the importance of providing information on the effectiveness of urban greening to drive its implementation in policy.

Research gaps exist in how to link changes in environmental exposures and thermal comfort to health and economic outcomes, going beyond estimates of mortality. This is especially challenging when exposures are non-specific (i.e. the actual environment to which a person is exposed is uncertain) or where outcomes are poorly measured (e.g. if they are not recorded in routine administrative data or health records or have detection bias issues) (Nazarian et al. 2022). This poses challenges for estimating the effects of urban adaptation on mental health.

3. Setting the Research Agenda

Priorities for future research in this Theme relate to how urban societies respond to a changing climate. Researchers working at IEDE within this Theme are always questioning how to approach both the mitigation of and adaptation to climate change, the integration of which is vital in the built environment context. That is why research at IEDE tries to provide a holistic understanding of the costs and benefits that each adaptation or mitigation measure may have on other dimensions, like health and economics in the HEROIC project. It also tries to inform decision makers by exploring the most practicable solutions in terms of adaptation and mitigation strategies for the UK and other countries, such as India or the countries in East Africa where research collaboration has been fostered by Wellcome-funded projects like CUSSH, SHUE (Sustainable Healthy Urban Environments) (https://www.ucl.ac.uk/bartlett/environmental-design/research-projects/2020/nov/sustainable-healthy-urban-environments-shue), Optihouse, HEROIC and 'Economic and Health Impact Assessment of Heat Adaptation Action: Case studies from India'. After all, these questions are closely tied to climate mitigation and adaptation policy, so working with policy makers and decision makers is vitally important to ensure the relevance and applicability of our work. How best to achieve co-production of research with potential research beneficiaries is an important question and is addressed by the PAICE project, which is working with the CCC and Greater London Authority on the co-impacts of net zero.

Figure 1. IEDE has deployed monitoring equipment across a variety of indoor and outdoor urban environments to measure the exposure of people to climate-related health hazards (Image credit: Oscar Brousse)

3.1 Modelling of urban climate and future adaptation solutions

The effect of cities on the local climate can be modelled at a scale of a few hundred metres (neighbourhood) or a few kilometres (whole cities and suburbs), a modelling scale appropriate to the atmospheric processes which govern urban climate. This permits a better understanding of how cities and the elements that compose them change the climate at a neighbourhood or regional scale (Heaviside et al. 2021). After making sure that models are performing realistically by comparing their outputs with weather observations obtained from national meteorological offices, satellites or people's contributions (Brousse et al. 2023), we can then represent how changing some of those elements can be beneficial or detrimental for building cities that are resilient to climate change. In particular, IEDE has long been interested in studying the environmental, health and economic benefits arising from green, blue and grey infrastructures – such as parks and green roofs, nearby water bodies or highly reflective materials, respectively (Simpson et al. 2023b; Simpson et al. 2024; Brousse et al. 2024; Moraes et al. 2024; Simpson, Brousse & Heaviside 2024).

To be able to study how green, grey and blue urban infrastructures would perform in a future climate, IEDE has been maintaining and developing its modelling capacity. The Thamesmead (London) case study of the CUSSH and CAMELLIA projects used both qualitative and quantitative participatory system dynamics models to explore the factors influencing the quality of the green, built and blue environment, and co-producing strategies for improving the use of urban natural space. Using a systems approach, they also developed strategic partnerships with stakeholders to understand perceptions and challenges related to water management, and collaborate to integrate models that represent the interacting components of the urban water cycle, supporting joint modelling of the water environment (O'Keeffe et al. 2022; Pluchinotta, Salvia & Zimmermann 2022; Pluchinotta et al. 2024; Prioreschi et al. 2024; Coletta et al. 2024a, 2024b). We have long-standing expertise with building physics modelling (e.g. DesignBuilder and EnergyPlus; also see chapters 1.6, 1.8), but to answer these questions at larger scales we have been increasingly using neighbourhood and urban-scale climate models to understand how common adaptation and mitigation strategies affect not only the indoor environment but also the urban outdoor environment of public spaces (Figure 2 and Figure 3). We have therefore developed in-house expertise in the use of regional climate models with embedded urban climate models that run at resolutions of a few hundred metres to a kilometre to study the impact of urban areas on the local climate and how to reduce its negative impacts at the city scale (e.g. using the Weather Research Forecasting (WRF) model, with in-built building physics schemes; see Simpson et al. 2023b; Simpson et al. 2024; Brousse et al. 2024; Moraes et al. 2024; Simpson, Brousse & Heaviside 2024). This offers several opportunities to study the current urban climate of cities including London, São Paulo, Kampala and Paris and propose solutions to reduce people's exposure to outdoor heat. But, as those models remain rather generic in their representation of the built-up environments and the vegetation that composes them, we are also expanding our modelling capacity to more local-scale urban climate modelling using computational fluid dynamics models that resolve the impact of urban environments and their variety of materials at a scale of a few metres to hundreds of metres (e.g. using ENVI-met). In doing so, IEDE will be capable of comprehensively investigating future pathways for building more sustainable and healthier cities.

Figure 2. What makes a place protective or not of heat? Urban climate walk organised by the Urban Heat Collective as an example of public engagement activity in East London. IEDE is involved in numerous public engagement activities and works closely with local inhabitants on issues related to climate change and health and how to mitigate them – like adding vegetation in urban areas (Image credit: Oscar Brousse)

3.2 Climate change, health and wellbeing

The World Health Organization has warned that climate change is the "single biggest health threat facing humanity". Our work investigates the climate change mitigation and adaptation measures and the possible health implications in the context of the United Nations Sustainable Development Goals.

Extremes of temperature affect the health, wellbeing and comfort of people, as well as their health. High temperatures have been shown to have an impact on patterns of mortality. Heat-related mortality is thought to be higher in cities due to a combination of greater exposure to high temperatures (through urban climate effects) and concentrations of vulnerability. Therefore, climate change is increasingly recognised as a health and wellbeing issue. Researchers at IEDE, in collaboration with LSHTM and UKHSA, have taken a leading role in research establishing the links between heat and health, especially in relation to urban climate effects and the effects of housing on health (see Chapter 1.4). This also allows us to better understand how heat acts as a threat to people in a different sense to other problems related to air pollution and water management – which are also climatically driven (Simpson, Brousse & Heaviside 2024).

3.3 Geospatial analysis

Geographic information system (GIS) analysis can be used to analyse and map high spatial resolution data in cities and investigate relationships between urban features and health while accounting for interactions with other psychosocial factors.

Recent work within the HEROIC project applied geospatial machine learning and image analysis to identify buildings with green roofs from aerial imagery. Green roofs can mitigate heat, increase biodiversity and attenuate stormwater, giving some of the benefits of natural vegetation in an urban context where ground space is scarce. To guide the design of more sustainable and climate-resilient buildings and neighbourhoods, there is a need to assess the existing status of green roof coverage and explore the potential for future implementation. Therefore, accurate information on the prevalence and characteristics of existing green roofs is required (Simpson et al. 2023a). In future, these techniques could be expanded to track progress on adaptation of the urban built environment more generally – including urban solar power installation, urban greening and roof albedo modification, which could inform climate adaptation policy.

In another study for the HEROIC project, geospatial data of the tree canopy coverage of London was combined with crowdsourced temperature data to estimate the effect of trees on air temperature using machine learning. From this, the health impacts of several realistic tree-planting scenarios for London were evaluated in terms of their potential reductions in heat-related mortality (Taylor et al. 2024). These novel techniques could be applied more widely to link tree-planting programmes with their environmental impact and therefore inform the business case for adaptation of the urban environment.

Figure 3. EDE learns from the present to build a better future for our next generations and prevent outdoor overheating (Image credit: Oscar Brousse)

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Expert workshops: Reflections and future research pathways

UCL IEDE Climate Change, Sustainability and Cities Workshop – CLD external workshop

Summary of the workshop

We held an online workshop including invited external experts on 23 May 2024. Participants were presented with a pre-made miniature causal loop diagram (CLD), co-designed by IEDE Theme members to explore the connections between urban greening and health. During the workshop, participants were invited to suggest changes to the diagram and had the opportunity to add or modify variables and connections in a facilitated group discussion. After collaboratively describing the causal structure of the problem using the CLD, participants were invited to identify directions for future research and connect them to the CLD.

The CLD from the workshop illustrates the systemic connections between urban greening, mental health and health outcomes (morbidity and mortality). The gaps and priorities for future research identified by the participants are highlighted in the green circles.

The resulting diagram illustrates that the benefits urban greening brings to mental and physical health occur through multiple interconnected pathways. One causal pathway involves excess heat, which affects mental and physical health both directly and through physical activity. Another pathway includes the amenity of greenspace, a variable we used to simplify a wide range of factors describing how green space is used (for active travel, for recreational sports, for relaxing) as well as its accessibility and how different forms of land cover (e.g. tree canopy, lawns, semi-wild grassland, blue spaces) are incorporated into urban green spaces. This simplification was necessary to keep the CLD small and manageable, since individually enumerating all different qualitative and quantitative aspects of amenity would otherwise dominate the workshop. The amenity of green space was identified as affecting mental and physical health directly as well as through physical activity. Additionally, policy-making and global climate change represent a wider set of context variables that influence the health directly and indirectly through the urban environment.

Table 1: Expert workshop participants list

Name	Affiliation
Shreya Banerjee	Indian Institute of Technology Jodhpur, India
Peter Crank	University of Waterloo, Canada
Purnamita Dasgupta	Institute of Economic Growth, New Delhi, India
Emma Hutchinson	London School of Hygiene and Tropical Medicine, United Kingdom
Peninah Murage	London School of Hygiene and Tropical Medicine, United Kingdom
Tania Sharmin	Welsh School of Architecture, Cardiff University

Six reinforcing loops were present in the CLD

Reinforcing Loop R1 – Urban greening reduces excess heat, but excess heat reduces urban greening. The rationale for this relationship is that urban greening has the well-known ability to reduce the air and surface temperature of cities, but excess heat can prevent the growth of plants especially if water is insufficient. Therefore, this negative reinforcing loop identifies that excess heat can itself be a barrier to urban greening in certain contexts, and therefore the ability of urban greening to address excess heat is not universal across all climates.

Reinforcing Loop R2 – Physical activity and mental health are directly mutually reinforcing. Their connection in this diagram identifies that any action that reinforces physical health can also improve mental health and vice versa.

Reinforcing Loop R3 – Evidence of green space use can support sustainable decision-/policy-making, which can lead to increasing amenity of green space which can create greater evidence of green space use. The reverse may occur, where green space with poor amenity, or without evidence of its use, will not be supported and may undermine broader sustainable decision-/policy-making. This loop overlaps with R4 and R5.

Reinforcing Loop R4 – Urban greening → amenity of green space → evidence of green space use → sustainable decision-/policy making → urban greening. This loop identifies that if urban greenspace is successfully implemented in a way that leads to its usefulness being evidenced, then this strengthens sustainable decision-/policy-making and therefore reinforces urban greening. Amenity of greenspace also has a directly reinforcing relationship with evidence of green space use and sustainable decision-/policy-making, which identifies how creating and collecting evidence of green space use represents a leverage point for expanding urban greening.

Reinforcing Loop R5 – Identifies that sustainable decision-/policy-making affects urban greening indirectly via changes to impervious surfaces as well as directly. This links into all other loops connecting sustainable decision-/policy-making with urban greening.

Reinforcing Loop R6 – Impervious surfaces increase excess heat, which creates a second reinforcing loop with a similar effect to R1.

The future research pathways identified by the workshop participants broadly relate to two aspects: quantification and appraisal, and justice and inclusion. For example, several of the identified research gaps highlighted the need for quantifying costs or benefits (e.g. "quantification of costs and benefits or urban greening", "dose responses of heat on mental health" or "dose responses of urban greening impact on health and well-being"). Participants emphasised that decision-making and policy are strongly informed by cost–benefit analysis methods, meaning that actions with poorly quantified costs and benefits are unlikely to be adopted into policy. More broadly, participants pointed to a need for geographical diversification of the evidence around greenspace, with much existing evidence relating to high-income countries and the Global North. A greater consideration of the variety of urban greening solutions that might be appropriate in different climates and geographies should also be pursued, going beyond the European and North American ideals of what parks and recreational spaces should be. The participants also highlighted research gaps around environmental justice and socioeconomic barriers to green space use, noting that urban greening is often considered in a top-down spatial framework that does not necessarily consider how accessible and usable green spaces are; they questioned relations of power within the urban environment, wondering who has control and influence over their living environment and who is excluded from decision-making processes.

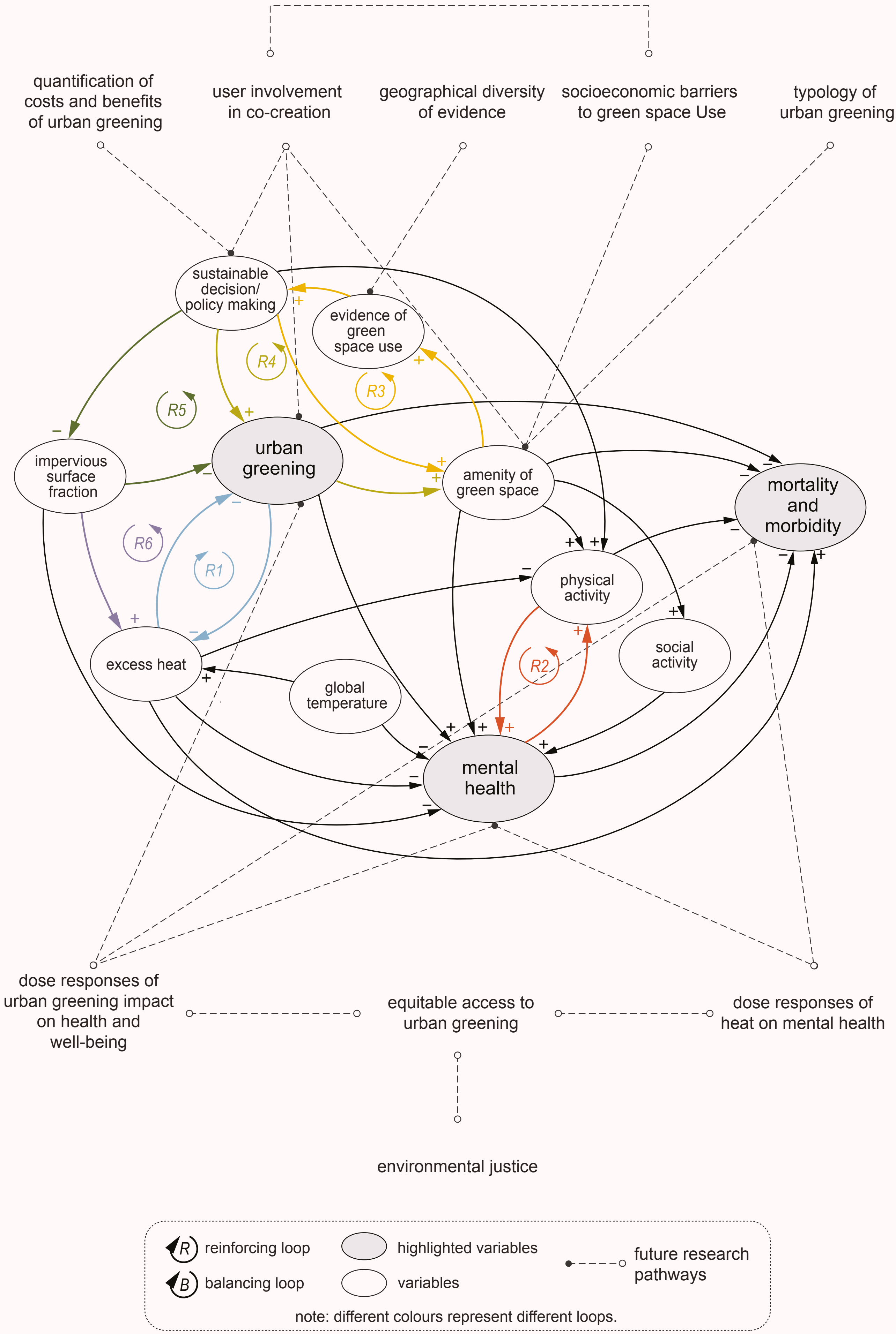

Figure 4. Causal loop diagram: Climate change, sustainability and cities (Image credit: Koko Zhou and Daijia Ke 2024)

THEME: SMART BUILDINGS AND DIGITAL ENGINEERING

Contributors: Guokai Chen, Cheng Cui, Flavia De Andrade Pereira, Virginia Gori, Kyriakos Katsigarakis, Ivan Korolija, Georgios Lilis, Dimitris Mavrokapnidis, Dimitrios Rovas, Rui Tang, Yuhong Wang (CLD expert)

1. Where We Are

The Smart Buildings and Digital Engineering (SBDE) Research Theme at the UCL Institute for Environmental Design and Engineering (IEDE) focuses on digitalisation and integrating and using digital technologies to support building design, construction and operation. The digital era has introduced new opportunities for developing and applying innovative modelling tools and research methods and for facilitating access to and utilisation of diverse data on buildings, building systems and occupants.

IEDE seeks to generate new knowledge and create impact through strategic research and teaching activities. A key challenge in achieving an effective and decarbonised built environment is the gap between the demand for and supply of a highly skilled workforce. This skills gap hinders the rapid adoption of digital technologies and the development of solutions for a sustainable, low-carbon future in the built environment. To address this challenge, IEDE developed a unique and highly technical MSc programme in Smart Buildings and Digital Engineering in early 2016, with the first cohort starting in the 2018/19 academic year.

With a focus on novel modelling techniques, advanced system functioning, building data collection, processing and data analytics, the programme explores how digital technologies can be utilised in building services engineering to support the design and operation of sustainable buildings. The programme suits graduates with an engineering background eager to gain an integrated perspective on buildings, their systems and users. The aim is to create a new generation of technology leaders capable of delivering high-performance solutions in the engineering design of building systems. Recent graduates of the programme have secured positions in large engineering consultancies or joined doctoral research programmes at top universities in the UK and globally.

While developing the MSc programme, IEDE members have also been actively researching and contributing new knowledge in this domain. Since 2016, the SBDE research group has rapidly grown into a dynamic team of over 15 researchers and academics. The SBDE Group has produced world-class research and engaged in national and international scientific communities. Group members have participated in research projects, collaboration activities and standardisation committees, and have organised conferences and events. They have significantly contributed to numerous research projects, advancing the SBDE field and benefiting many stakeholders, including building designers, space occupiers, property owners, facility managers, grid planners and policy makers.

The SBDE Theme research activities can be broadly categorised into three streams – (1) Smart Buildings, (2) Digital Engineering and (3) Advanced Building and Systems Modelling – with strong intersection and cross-collaboration among these.

1.1 Smart Buildings

The Smart Buildings stream focuses on data-driven modelling and methodological approaches when tackling the challenges of developing and delivering solutions for smart buildings. The definition of the data-driven smart building in the SBDE Theme is aligned with the definition given by International Energy Agency (IEA) Annex 81: “A building that uses digitalisation technologies to dynamically optimise its operation, where optimisation objectives typically relate to site energy use, IEQ, and occupant experience” (IEA 2020). The emphases of the core stream activities are building operation optimisation, fault detection and diagnostics, demand response and achieving grid-interactive buildings by applying various aspects of artificial intelligence (AI) technologies on the numerous available data obtained or collected from different sources – for example, building management systems (BMS) and the Internet of Things (IoT).

One example of the research activity in this stream is the Horizon Europe BuildON project (BuildON 2024), funded by the European Commission, which seeks to change the concept of buildings from a static perspective to a flexible ‘building-as-a-service’ approach by developing technologies for achieving improved energy performance applicable to the broadest range of building typologies and smart readiness levels. A toolbox is developed to provide affordable, adaptive, easily accessible and close-to-market services for continuous monitoring and optimisation of buildings’ performance. The user-friendly toolset will allow more effective energy use, supported by an interoperability framework for the integration of heterogeneous building assets that rely on scalable AI-based solutions for monitoring, benchmarking and fault detection while optimising energy performance.

The group has been active in knowledge and expertise transfer to industry through participation in Knowledge Transfer Partnership (KTP) projects or projects directly funded by industry partners. For example, in an Arup-funded project, the group developed Modelica models to analyse the energy use of different fan-coil control strategies in tertiary heating/cooling loops. A KTP project, in partnership with Tesco PLC, focused on developing a 'Smart Tool for Electrification and Decarbonisation of Stores' to forecast changes in store electricity demand due to decarbonising technologies and mitigate the challenges due to the electrification of heat and transport systems exceeding the local constraints of distribution power networks. The tool focuses on refrigeration systems (the largest energy consumer in stores) and aims to facilitate heating system electrification by applying refrigeration system heat recovery. It is based on a first-principle model of a CO2 refrigeration plant that uses monitored high-frequency plant data to predict electricity use and the amount of recoverable heat under typical operation scenarios and modified conditions aiming to increase recoverable heat.

Another KTP project, collaborating with ECD Architects Ltd, empowers them to deploy already-established retrofit methodologies at scale and address the surging demand for processing large amounts of data in retrofitting projects. This project aims to adopt AI and machine learning practices to automate data processing with enhanced efficiency and quality in large-scale retrofit projects and build predictive models to aid in the analysis and decision-making of retrofit measures.

In addition to participating in EU-funded and KTP projects, the SBDE team has actively contributed to the IEA Energy in Buildings and Communities (EBC) programme. This involvement has contributed significantly to Annex 81 on Data-Driven Smart Buildings (IEA 2020), in which the team members co-led a subtask, and will contribute to the upcoming Annex 96 on Grid Integrated Control of Buildings.

1.2 Digital Engineering

The Digital Engineering stream aims to develop knowledge and tools for digital building delivery. The research activities within this stream focus on three main aspects: building information modelling (BIM), knowledge graphs, and platforms and tools. Defined in ISO 19650-1:2019 as the: "Use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions" (ISO 2018), BIM is expanded in model checking and assurance as well as in BIM to building energy modelling (BEM) applications. Knowledge graphs are applied to organise the built asset information and can be used to deploy portable analytics and semantics-driven control. To support the delivery of analytics and control, a digital twin platform has been developed, as well as several tools to support this.

These challenges are being addressed in the EU-funded H2020 COGITO project. Within COGITO, innovative data integration methods and tools have been developed to create digital twins that combine 'static' BIM data with 'dynamic' data. A key innovation is the enhanced interoperability among various components within the digital twin platform, developed by the UCL team. This platform serves as data integration middleware, gathering necessary data from multiple streams and supporting workflow and process monitoring, defect detection, and health and safety applications. The prototype has been successfully tested at three construction sites across Europe.

The SBDE Group contributed to the DigiBUILD project (DigiBUILD Project 2024), funded under the EU's Horizon Europe programme, which focuses on high-quality data-driven services for a digital built environment to achieve a climate-neutral building stock. The work aims to provide an open, interoperable and cloud-based toolbox to transform current isolated buildings into digital, interoperable and smarter ones based on consistent and reliable data exchange processes and tools. The SBDE's significant activities include defining data models and their ontological representations, developing data collection and integration tools, and upscaling the concept of the digital building twin. The tools were applied and tested in the pilot case study, where digital twins were created for two UCL East buildings.

The SBDE team also contributes to the transferability of expertise through leading training networks such as CBIM (CBIM 2020) – a European training network on cloud-based BIM. CBIM has developed a training-by-research programme to support the delivery of improved BIM-based digital twinning technologies. The primary outcomes include portable analytics frameworks, semantic enrichment tools and the development of blockchain-enabled common data environments.

International collaboration on defining and addressing the latest challenges in the built environment domain in this stream is through participation in the IEA-EBC programme, Annex 91 on Open BIM for Energy Efficient Buildings (IEA 2024).

1.3 Advanced Building and Systems Modelling

The Advanced Building and Systems Modelling stream focuses on modelling across scales and the use of modelling across the various phases of a building's lifecycle, from early conceptual design to operational stages. The modelling scale starts with component-level modelling, where the effectiveness of individual components is evaluated. Modelling and simulation of heating, ventilation, air conditioning and refrigeration systems, either as part of a building or in isolation, help identify malfunctioning states, explore opportunities to improve system functioning and derive solutions to shift overall performance towards low-energy and low-carbon operation. Lastly, methods and tools have been developed and applied to evaluate the energy behaviour and resilience of large urban areas and building stock segments.

In the 2020 BIMERR project (BIMERR 2020), funded by the European Commission, the potential of adopting digital technologies to accelerate renovation pathways and better manage large and complex projects has been recognised. The key output was a BIM platform that supports renovation workflows and decision-making. This toolkit comprises multiple modules that aid in the automated creation of BIM models, explore renovation strategies by considering their impact on building performance, optimise design and construction processes, and facilitate high-quality information exchange among Architectural, Engineering and Construction stakeholders.

The LSOM project (Greater London Authority 2024), funded by the Greater London Authority, developed an online solar mapping tool that allows Londoners to evaluate the potential for photovoltaic panels and solar thermal installations on both structures and land around London. Utilising high-density light detection and ranging (LiDAR) data from the Environment Agency, converted to a digital surface model, the annual solar radiation is calculated and aggregated into a regular grid dataset with cells of 0.5m x 0.5m. This includes all objects captured by LiDAR (trees, vegetation, land, buildings) for an area of approximately 2,500km^2 encircled by the M25 motorway.

Another project (UKRI 2024) funded by the UK Engineering and Physical Sciences Research Council works towards a physics-informed machine learning modelling methodology targeting multi-scale building systems. The method facilitates the development of energy-flexible and resilient buildings and comprehensively assesses different control strategies before implementation. The modelling approach combines machine learning and physics-based methods to ensure reliable and interpretable modelling outputs, especially in large-scale, multi-building contexts.

A significant part of stream activities is the development of stock-level modelling platforms: the Modelling Platform for Schools (MPS) and SimStock. The school-specific MPS (Schwartz et al. 2022) and the more generic SimStock are modelling platforms combining data from multiple sources to automatically generate dynamic building energy simulation models. These models characterise the stock's energy use and assess the impact of improved regulations, technology enhancements and refurbishment interventions across an extensive building portfolio. Both platforms are applied in various research projects, as part of methodologies in PhD projects, and as teaching tools in MSc modules.

In the context of the Advanced Building and System Modelling stream, the SBDE Group has active involvement in Annex 82 on Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems (IEA 2022) and Annex 83 on Demand Management of Buildings in Thermal Networks (IEA 2023).

2. Research Challenges

IEDE's SBDE Group focuses on developing novel methodological approaches to improve building performance. Working towards the transition of the entire building stock into the smart realm, the group invests significant effort into understanding and addressing the challenges of digitalising the built environment, including data representation, data interoperability, information modelling and data-driven analytics. Furthermore, the SBDE Group develops new modelling methods to tackle issues related to predicting building and system operations during early design stages, evaluating in situ equipment performance and assessing the impact of potential improvements. The group often develops new tools and platforms to address these core challenges, working across various scales and domains.

A vital component of smart buildings is the automation and control of building systems. Commonly used rule-based control methods have demonstrated limitations in meeting the emerging demands for energy efficiency, grid interactivity and coordination with other energy system sectors. Although advanced technologies such as model-predictive control (MPC) and reinforcement learning (RL) have shown their strengths, they are still not widely adopted in the real world due to complexity, costs and physical infrastructure concerns. The SBDE team has conducted pioneering research in these areas. For example, they have benchmarked RL control techniques to identify superior methods for energy-efficient building operations (Wu et al. 2024), demonstrated energy-efficient controls that include occupants in the control loop to coordinate their behaviour with energy-efficient technologies (Tang, Wang & Sun 2021), and deployed the Smart Readiness Indicator (SRI) to assess the performance of individual buildings or building stocks comprehensively (Kourgiozou et al. 2023).

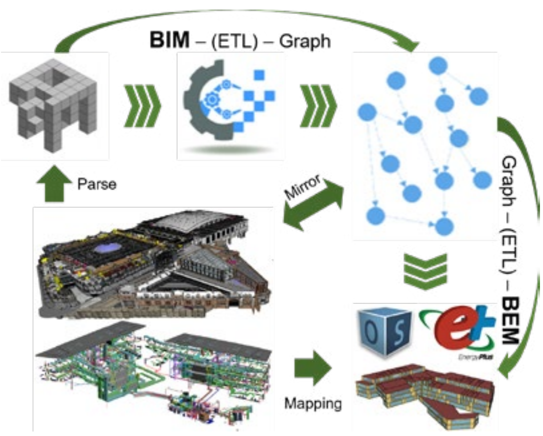

Figure 1. Concept map of BIM2BEM framework (Image credit: Authors)

Digitalising the built environment in the context of smart buildings requires a shift from 'static' building data to 'dynamic' digital twins. Broadly defined as real-time digital representations of physical assets, digital twins require a connection between static and real-time data. However, building information is usually stored in different formats across the lifecycle, making data integration challenging (Mavrokapnidis et al. 2021). Static building data, such as building geometry typically found in BIM, can be used to generate BEM, yet this process is often complex due to low-quality data. The SBDE Group is investigating a novel ontology-based BIM2BEM framework (Figure 1) that leverages the power of knowledge graphs to facilitate data integration and automate the generation of building energy models. A suite of extract, transform and load validation and enrichment tools have been developed to manage varying levels of data quality across different building sites. This framework and toolchain are essential for generating the digital twin of UCL's One Pool Street building, as illustrated in Figure 2.

Figure 2. UCL East One Pool Street digital twin (Image credit: Authors)

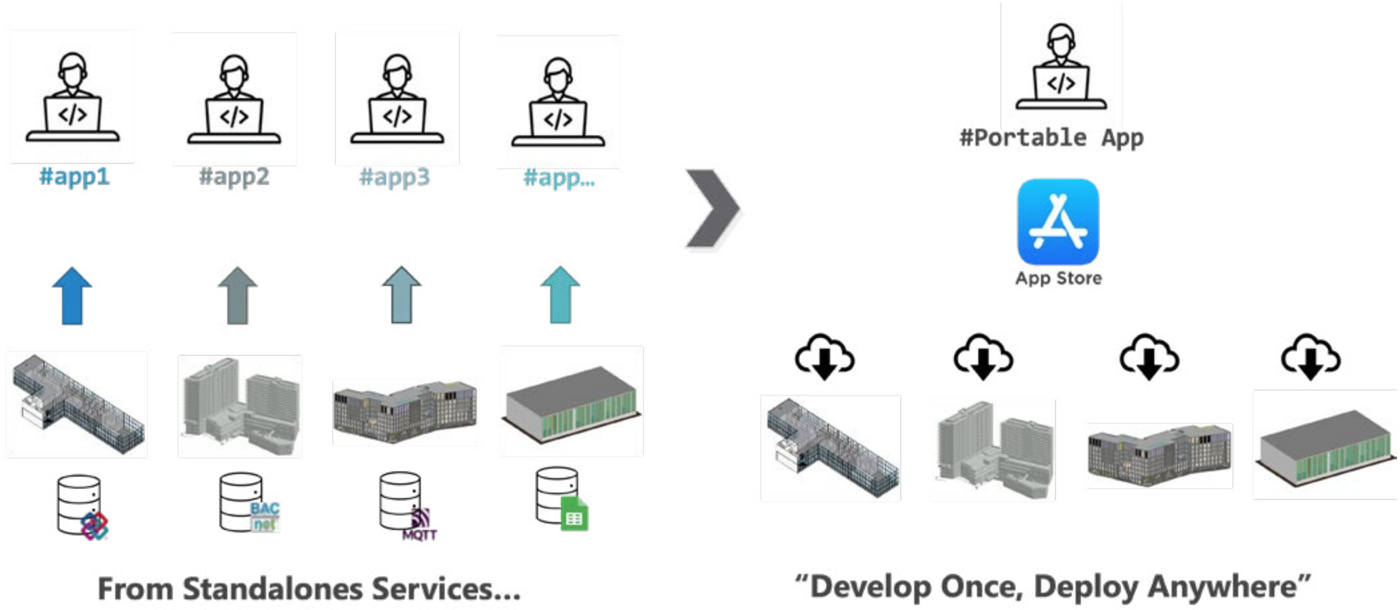

Figure 3. SeeQ enables the deployment of a portable application across multiple buildings (Image credit: Authors)

Data integration and normalisation are prerequisites for building energy model generation and for configuring data-driven services that provide insights into building operations and guide decision-making to achieve operational objectives. Research has shown that data-driven services are still developed on a standalone basis, require manual configuration across different buildings and do not scale well. To overcome these challenges, the SBDE Group has proposed SeeQ (Mavrokapnidis et al. 2023b), a portable programming model promoting the 'write once, deploy anywhere' paradigm (Figure 3). Tested in applications such as fault detection and diagnosis (Mavrokapnidis et al. 2023a), KPIs, virtual metering and machine learning-based forecasting, SeeQ has shown a 90% reduction in configuration and deployment time, offering significant benefits for large-scale building portfolios.

Furthermore, the SBDE Group's research investigates a combination of different advanced modelling approaches (i.e. white box, state space and black box). For example, resistance-capacitance-based models, widely used in MPC for their optimal complexity, require further evaluation across diverse scenarios (Chen et al. 2022). A major challenge is optimising the distribution of thermal energy in rapidly expanding district heating networks. In-depth white-box modelling and realistic controllers (Chen et al. 2023) can enhance these networks, particularly the fourth-generation systems that integrate photovoltaic thermal (PVT) panels (Kang, Korolija & Rovas 2021) and storage technologies (Kang, Korolija & Rovas 2022) in high-energy-density areas. The group used a co-simulation setup (Modelica and EnergyPlus) to assess the technical feasibility of solar PVT district heating in new-builds, focusing on advanced control systems to improve efficiency and sustainability (Chen et al. 2023).

3. Setting the Research Agenda

Discussions identified future research pathways grouped along four key themes that should be considered as part of future research:

1) Data availability (bottom right quadrant in Figure 4) is key to ensuring transition in data-driven approaches. Making data available according to FAIR (findable, accessible, interoperable, reusable) principles remains a research challenge. If research is to advance, good-quality data needs to be made readily discoverable and available for secondary use. There is extensive data collection today, but such data is collected for specific uses. Curating and publishing high-quality datasets can lower the threshold for developing new data-driven algorithms and tools. Capturing relevant essential variables in these datasets is crucial to ensure their reusability. When considering data preparation for reuse, it is important to understand the specific uses of datasets to identify a complete set of requirements. A data-readiness indicator could be introduced to highlight high-quality data and help identify the suitability of datasets for specific types of secondary use. From the participatory workshops held by the members of this group, it was also found that making the data discoverable remains a significant challenge – at present, much of the data is stored in institutional repositories. A registry like re3data (re3data.org 2024) is useful, but creating data directories with high-quality, reusable datasets can be quite beneficial and help ensure equitable access. As always with data sharing, metadata is as important as the data itself – using standardised approaches to structure metadata is crucial to enhance data discoverability. In all cases, but especially when personal data is concerned, there are challenges in how this data can be packaged and made available. Ensuring that privacy concerns and data access (R3) are handled in line with ethical principles and relevant regulations like the GDPR (R2) is key. Research into sovereign data (R3) sharing approaches is crucial in this regard; such approaches are implemented using the concept of data spaces, but the means and approach to achieve this will remain an exciting research challenge. This is likely to significantly affect the built environment, especially when information sharing is required in contractual data exchanges, which are likely to become pivotal in demand response. Addressing these issues will increase data availability and positively affect the development of data-driven approaches.

2) Evidence (top left quadrant in Figure 4). Smart building technologies or data-driven modelling approaches are still not widely adopted. One of the challenges is the unclear value proposition and implementation pathways. Creating an evidence base that highlights the benefits and provides relevant, contextualised information is key to accelerating the adoption of such approaches (and the benefits). Further research is required to provide an evidence base and credible guidance. Collaboration between government, industry and academia (R1) is fundamental in this domain. Collecting case studies is valuable in understanding the benefits and drawbacks associated with specific technologies and/or approaches (UCL 2024). The use of building rating schemes and digital-ready certification can drive the adoption of smart building technologies (B1). Examples include the SRI (Directorate-General for Energy 2020), with more research needed to understand credible ‘smart’ implementation pathways to ensure impact. In this regard, less is sometimes more. More technology is not always the answer – taking a whole-system perspective and a just enough more nuanced and balanced approach to delivery is likely to have a more significant impact. The concept of sufficiency emerges as important and should be embedded in current processes. This is already being discussed in the context of energy sufficiency, but it has broader practical and philosophical implications that need to be considered.

3) Applications (top right quadrant in Figure 4). The collection of data is not an end in itself, but the insights generated from the data are what create and derive value. Focusing on understanding where the value lies and how to deliver this value remains a significant research area. Following the concept of sufficiency, we need to work backwards from services, identifying data and information requirements that support insights. Many applications (e.g. monitoring, fault detection and diagnostics, or advanced control) remain significant. New operational scenarios linked to decarbonisation and smart grids will likely require significant adaptations of our buildings and new grid-

interactive controls. These are not the only applications: facility managers and energy managers have specific needs associated with specific systems or processes (e.g. refrigeration in supermarkets), and this will require novel solutions. Interactivity of assets across scales – from systems to buildings to districts to cities – will become more significant, and more dynamic approaches that consider some of the interoperability challenges are required. More importantly, for any of the applications to be impactful, their deployment should be replicable with minimal effort. For this reason, application portability is crucial. Knowledge graphs and methods like transfer learning are likely to provide some insights into how this can be achieved.

4) Enabling (bottom left quadrant in Figure 4). Such applications need to be user-friendly when they have interfaces. If one looks at the state of the industry tools available, it is very clear that these tools are created by engineers for engineers. Focusing on user experience and supporting a specific purpose is an important area of research and development. There is significant hype around the use of machine learning and AI, which has only been further exacerbated by the new generation of transformer architectures and large language models. The industry needs useful examples of how to use these technologies, and researchers should provide such tools and training. Training is more broadly relevant: the skills required to deliver the digital transformation transcend traditional boundaries, from building services to advanced energy and information modelling to information and communication technologies. The MSc in Smart Buildings and Digital Engineering exemplifies this, aiming to create a future-proof graduate profile. Our research findings will likely evolve our understanding of what this profile will be and how to have resilient graduates who can create the SBDE future. Training is required to install digital technologies; in this regard, apprenticeships are also likely to be very significant.

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Expert workshops: Reflections and future research pathways

The complexity of understanding and influencing the built environment stems from multiple actors and factors, and their complex interplay. This complexity is why single-discipline approaches to understanding challenges in the built environment have failed to create impactful solutions – the reason being that such approaches focus only on a small part of the problem at hand and miss essential parameters that are hard to measure or estimate, or miss confounding variables. Having such broad understanding and engagement across disciplines is important to address built environment challenges like the existing building stock's decarbonisation of energy supply through the increasing use of renewable energy sources (R4). The scale of the complexity and the challenge can be understood from the viewpoint of several recent UK and international policies that did not adequately consider the social or technical dimensions and their interactions, leading to low uptake, complex processes and, ultimately, little impact – for example, the UK Green Deal, introduced in 2013 and discontinued in 2015. Taking a transdisciplinary view helps address such challenges, with several benefits, including integrating knowledge and methods across domains; supporting collaboration and co-creation from stakeholders to understand their perspectives and needs; and taking an outcome-focused and context-specific perspective. The use of system dynamics (SD) and causal loop diagrams (CLDs) is one such approach, frequently used in this context. CLDs help capture the complex interplay and help understand the interplay among factors. The SD/CLD approach has often been used to understand the challenges and opportunities in complex systems; here, it is used to discover future research pathways and research challenges on a 10-year horizon.

As the preceding discussion highlighted, the Smart Buildings and Digital Engineering (SBDE) Theme focuses on understanding how digitalisation can help shape and improve the built environment of the future. Such future pathways were the subject of a co-creation session held with SBDE Group members; to keep the discussion manageable, we focused primarily on buildings, although such an exercise can and should be repeated for other built asset classes. The discussion focused on the following research question:

How can the integration of smart building technologies and digital engineering practices enhance energy efficiency and occupant wellbeing while addressing potential ethical and privacy concerns in buildings and urban environments?

The question helped set the context for the participatory session and supported focusing the scope, although the framing of the question was intentionally broad to accommodate diverse views and perspectives. The participatory session focused on understanding future research pathways within the SBDE Research Theme. The session benefited from access to insights from similar international activities. In addition, the co-authors of this chapter have recently participated in broader international activities looking at understanding future research pathways within the SBDE Research Theme. Notably, members of the group run two sessions within the International Energy Agency (IEA-EBC) Annex 81 project on Data-Driven Smart Buildings and participated in a BauHOW5 event held at ETH Zurich, with representatives from the five strongest architectural engineering departments in Europe. The findings of these sessions (attended by more than 100 international researchers) were fed into the participatory session, which helped ensure that a wide range of opinions and perspectives were captured. Discussions identified key themes and complex system interactions, as shown concisely in Figure 4.

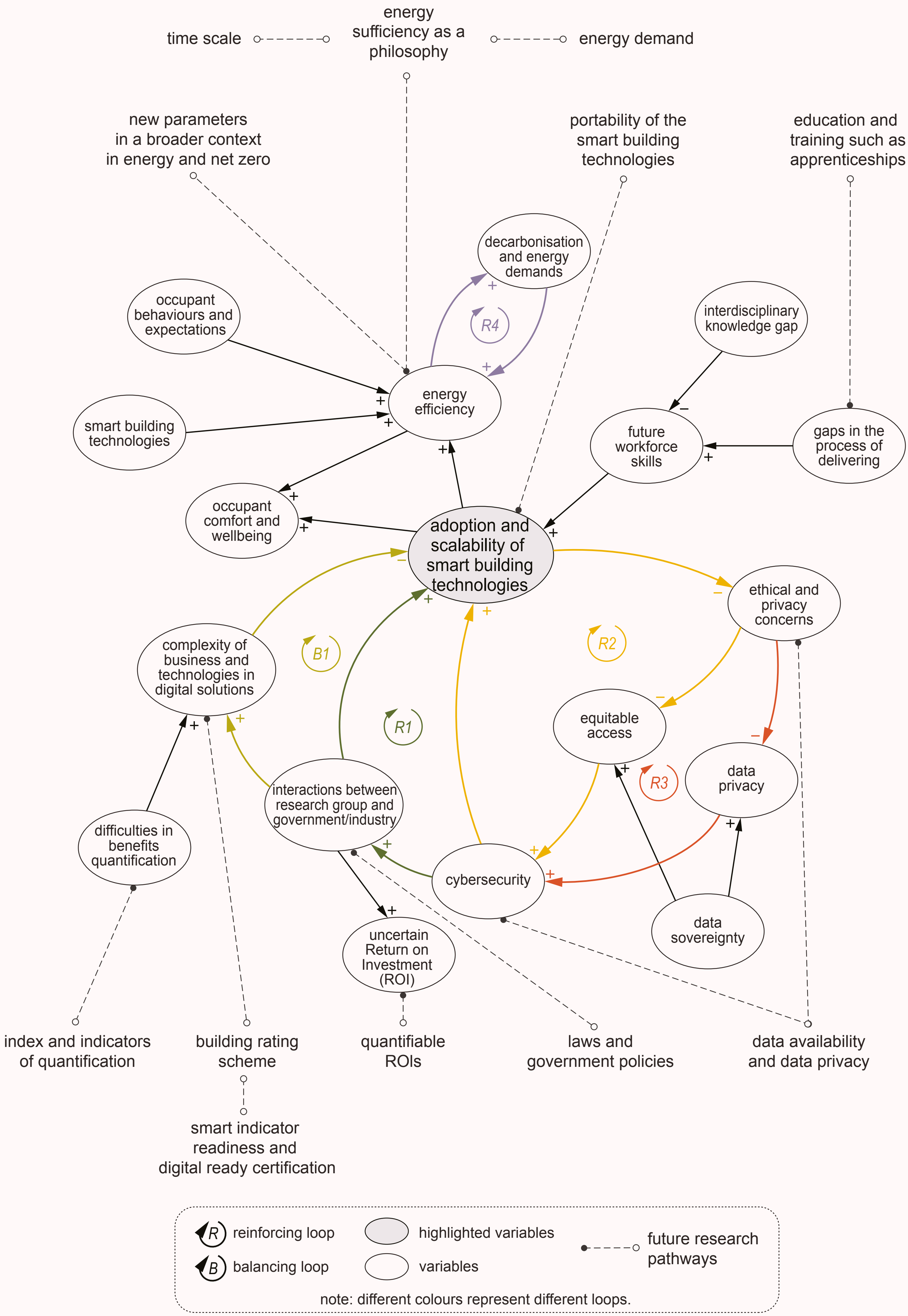
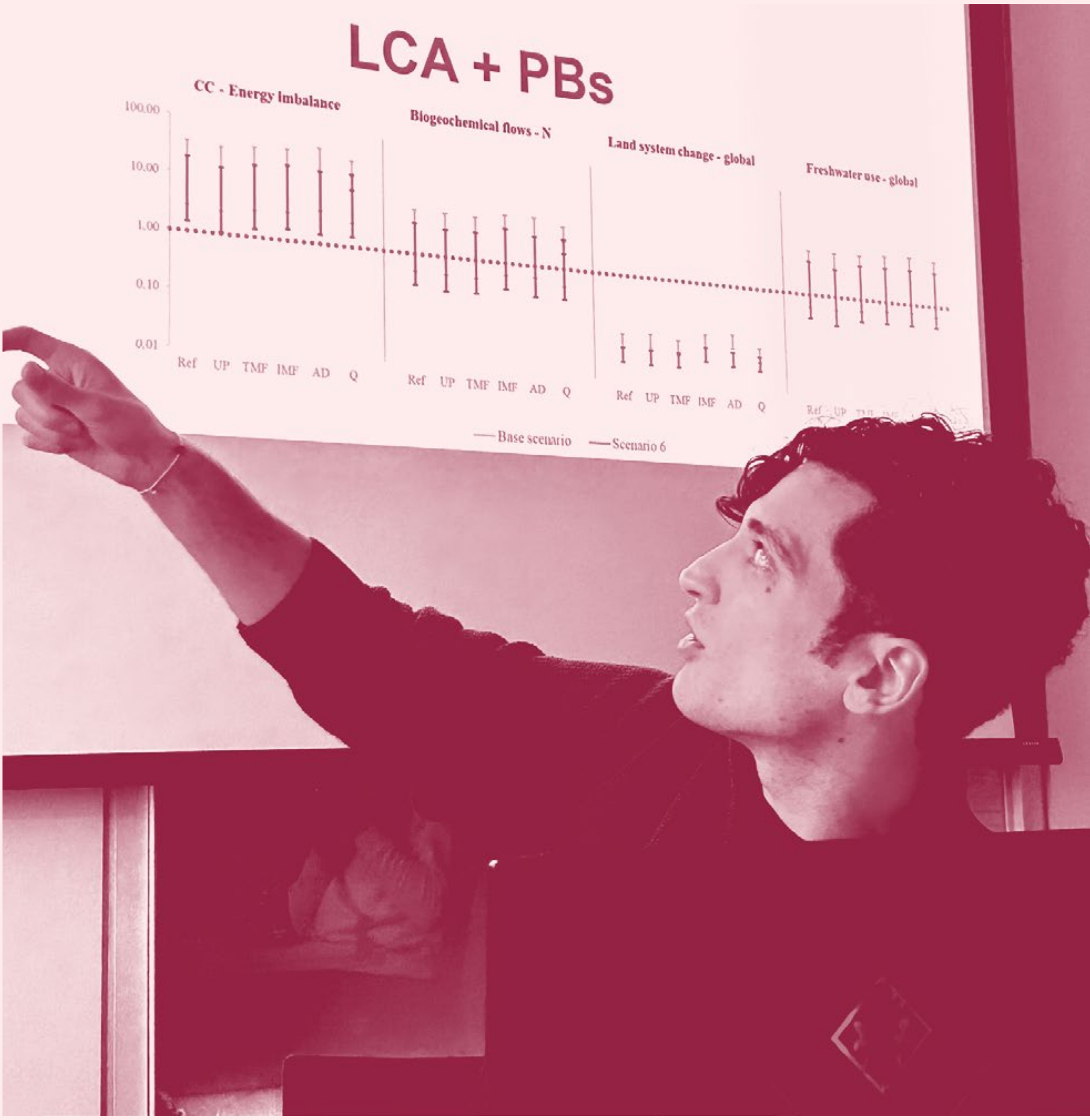


Figure 4. Causal loop diagram: Smart buildings and digital engineering (Image credit: Yuhong Wang and Daijia Ke 2024)

THEME: LIFE CYCLE ASSESSMENT AND CIRCULAR ECONOMY

Contributors: Yair Schwartz, Reham Alasmar, Ben Croxford, Craig Robertson, Eleni Davidson, Simon Vakeva-Baird, Seyma Atik, Sahar Nava, Marios Kordilas, Yuhong Wang



1. Where We Are

Building performance improvement efforts have traditionally focused on the operational performance of buildings (i.e. the performance of the building it is in use). The environmental impact of the built environment, however, is the result of processes that occur throughout their whole lifecycle – construction, usage and demolition or reuse.

Life Cycle Assessment (LCA) is a systematic method used to analyse the environmental impacts of buildings throughout their lives. This includes all lifecycle stages, from raw material extraction, production, construction, use and maintenance to end of life, disposal or recycling. The standards governing its use are ISO 14040 and ISO 14044 (ISO 14040 2006). Circular economy (CE) is a complementary mechanism system that aims to minimise waste and make the most of building materials and resources. It promotes recycling and recovering of building components, in contrast with the traditional 'linear economy', which follows a 'take, make, dispose' approach. While LCA provides insights into the environmental impacts of building materials and impacts resulted by the consumption of energy while the building is used, CE strategies focus on reducing these environmental impacts through better design, material selection, waste management and reuse or recycling strategies. Integrating LCA and CE principles can help create buildings with minimised carbon footprints.

Responding to policy and industry concerns, early days at the UCL Institute for Environmental Design and Engineering (IEDE) focused on research endeavours looking into the operational aspects of buildings. IEDE built an extensive portfolio of research focusing on energy efficiency in buildings, indoor air quality, comfort and more. However, acknowledging that building performance goes beyond the use scale, the Institute quickly expanded its research scope with projects looking at the lifecycle and circularity potential of buildings.

Early projects on LCA included PhD research projects, looking into themes such as the lifecycle carbon footprint of higher education buildings redevelopment, the question of refurbishment or replacement of existing buildings from a LCA perspective, and the lifecycle carbon and cost of the refurbishments of schools. These projects highlighted IEDE capabilities in adapting to emerging Research Themes, expanding its research expertise and establishing strong relationships with industrial partners. It also strengthened the Institute's reputation as an important research powerhouse in buildings performance.

A decision was made to establish the LCA-CE Research Group in 2022. The team comprises the Institute's LCA & CE PhD students, research associates and academics. Activities include cross-institutional seminars and workshops, support for PhD students and preparing research proposals and bids. Echoing the IEDE multidisciplinary ethos, the team incorporates a blend of advanced research methods and techniques.

The team aims to expand its activities and built its reputation as an established source of research and knowledge on LCA & CE in the built environment. To do so, the team has set up priorities and is focused on the following areas:

1. **Research:** The team has set an aim to become a prominent research hub on LCA & CE and has been actively seeking and securing collaborations and funded projects with both leading companies and potential industrial partners, as well as governmental and legislative bodies. Focus has also been placed on writing bids and taking part in grant applications for national and international research councils.
2. **Networking:** Following its formation, the LCA-CE team has established relationships with other research groups with similar interests, initiating and taking part in workshops, as well as hosting speakers from LCA & CE-related groups such as the UCL Circular Cities Research Hub, the Center for the Built Environment at UC Berkeley, the Architectural Facades and Products (AF&P) Research Group at TU Delft and others.
3. **Teaching:** The team sees great opportunity in sharing knowledge and developing emerging expertise around LCA & CE. Over the past few years, team members have delivered guest lectures and seminars on various modules and courses across The Bartlett. These efforts peaked with the development and delivery of the first whole lifecycle module in the Institute, as part of the Sustainable Built Environments Energy and Resources undergraduate degree, which was delivered in 2024 for the first time.

4. **Supporting the IEDE community:** The LCA-CE group organises a range of activities to support members in their professional work and research. The group is a pivotal platform for discussions on ongoing PhD research projects across UCL. Through this platform, researchers gain an invaluable opportunity to share their research, exchange ideas, receive feedback from peers and experienced academics, and foster collaborations for future projects.

The group's activities are wide-ranging. Some of these include:

1.1 Policy and protocols

CIBSE TM65 (TM65 2021)

TM65 (Figure 1), outlines a methodology for calculating embodied carbon in building services. The document guides the use of environmental product declarations (EPDs) for assessment and provides carbon estimation methods when EPDs are unavailable. This guidance was developed by CIBSE in collaboration with leading industry and academic experts, including contributions from Dr Yair Schwartz, who leads the LCA & CE Research Theme.

The UK Net Zero Carbon Buildings Standard (UKNZCBS 2023)

The UKNZCBS is an initiative to develop the country's first net zero carbon protocol for all major building types. The standard is a cross-industry effort, which is developed col-laboratively with leading practices, environmentally minded organisations and academ-ics, including staff from IEDE.

1.2 Innovation and technology transfer

Hawkins\Brown Emission Reduction Tool – H\B:ERT (UCL 2018)

Dr Yair Schwartz partnered with Hawkins\Brown Architects to create H\B:ERT – a user-friendly Revit-based tool (Figure 2) that enables design teams to quickly analyse and visualise the embodied carbon emissions of various building components and materials throughout the design process. H\B:ERT is widely used by practitioners, students and others globally, with thousands of downloads to date.

Figure 1. TM65: Embodied carbon in building services: A calculation methodology (Image credit: TM65 2021)

Figure 2. H\B:ERT Emission reduction tool developed by IEDE and Hawkins\ Brown. (Image: Courtesy of Hawkins\ Brown Architects, © Adrian Lambert)

UCL Personal Carbon Calculator

The UCL Personal Carbon Calculator helps individuals estimate and reduce their personal carbon footprint. This user-friendly tool assesses emissions from household energy, transportation, diet, goods, services and waste. By inputting data about daily activities, users receive real-time feedback on their emissions. Developed by Dr Yair Schwartz, the calculator offers a personalised view of carbon emission patterns and allows users to track their emissions over time, enhancing their understanding of their environmental impact.

1.3 Community outreach

A Participatory Life Cycle Sustainability Assessment Framework for the Appraisal of Estate Regeneration Schemes (Ms Sahar Nava)

This project engages different stakeholders to reflect their priorities in estate regeneration schemes. Since decision-making on housing estate regeneration in the UK is often driven by economic and energy-centric incentives, a holistic assessment method for building sustainability is used, including environmental and socioeconomic impacts; this is known as a Life Cycle Sustainability Assessment (LCSA). Overseen by Ms Sahar Nava, the study employs workshops, interviews with stakeholders and community members, surveys and questionnaires to establish a framework for a participatory LCSA.

LCA in Stakeholders' Perspectives: Early-design stakeholder engagement for healthy net zero buildings (Mr Simon Vakeva-Baird)

Early-stage building design can utilise participatory stakeholder engagement methods alongside building modelling and simulation tools to balance carbon, environmental, economic and social objectives. This project explores stakeholder-oriented design activities by using live case studies. A participatory approach involved stakeholders from technical and non-technical backgrounds using a mixed-methods research approach. In collaboration with Feilden Clegg Bradley Studios, visual dashboards and interactive workshops effectively conveyed stakeholder knowledge and informed decision-making through iterative modelling and simulation.

1.4 Projects and industrial partnerships, nationally and internationally

Delivering Net Zero Carbon: A guide for architects (Allford Hall Monaghan Morris (AHMM) and the IEDE Knowledge Transfer Partnership (KTP)) (IEDE 2022)

The two-year KTP was focused on the opportunities and implications of developing net zero carbon large-scale, mixed-use, urban, commercially driven and densely occupied buildings. The project was run by Dr Simon Hatherley in collaboration with Prof. Dejan Mumovic, Dr Esfandiar Burman, Dr Yair Schwartz and Dr Craig Robertson, Head of Sustainability and Employee Director at AHMM. The guidance (Figure 3) has been written to define net zero in such a way as to help architects to improve their knowledge, distil thinking and change the design process to that end.

Figure 3. AHMM and IEDE KTP guide, 'Delivering Net Zero in Use' (Image credit: AHMM, 2023)

Figure 4. UCL's partnership with the National Trust, and the key outputs of embodied carbon emissions of construction projects in the Trust (Image credit: UCL 2022)

Refurbish or Reuse (Hawkins\Brown and EPSRC**)**

Funded by the Engineering and Physical Sciences Research Council (EPSRC), the study developed a computational method, trying to understand whether the optimum refurbishment of existing buildings is preferable to their optimum replacement, in respect of lifecycle performance. The project estimated and compared both the lifecycle environmental and economic benefits of UK residential building refurbishments and their replacements.

Looking After What We've Got (Dr Yair Schwartz, Dr Esfandiar Burman, Ms Reham Alasmar, National Trust) (UCL 2022)

A partnership with the National Trust, UCL's Higher Education Innovation Fund and IEDE to set up recommendations for integrating embodied carbon analysis and reporting, as part of the National Trust's construction, refurbishment and maintenance activities. The project identified unique opportunities for tracking and reducing the carbon footprint of construction projects in the Trust. The report (Figure 4) concluded with a series of strategic recommendations, to enhance the Trust's embodied carbon environmental performance.

LCA of Higher Education Facilities (Ms Eleni Davidson with Feilden Clegg Bradley Studios)

Funded by the EPSRC, this project aimed to minimise the environmental impact of university buildings throughout their entire lifecycle. The project involved engaging stakeholders from diverse backgrounds who were working on real-world case studies of university buildings. This participatory approach ensured that the strategies developed were both comprehensive and practical, providing evidence-based policy recommendations to support the adoption of sustainable practices in the education sector (Davidson et al. 2024).

Decarbonisation Pathways for the Jordanian Housing Stock through Life Cycle Assessment and Optimisation (Ms Reham Alasmar)

This study investigated the intricate relationship between embodied and operational emissions in the Jordanian housing stock and evaluated the feasibility of zero carbon performance. The stock's current and future performance were examined, and refurbishment measures packages were developed and tested, considering both embodied and operational emissions simultaneously. The study resulted in a set of recommendations to policy makers in Jordan, and will hopefully lead to further research, looking into the construction supply chains in Jordan.

1.5 International collaborations

Economy Lab (UCL CircEL)

A joint initiative arising from a collaboration between Prof. Ben Croxford (IEDE), Dr Teresa Domenech (Institute for Sustainable Resources – ISR), Prof. Julia Stegemann (Department of Civil, Environmental & Geomatic Engineering – CEGE) and the Ellen MacArthur Foundation. This partnership led to the formation of the UCL Circular Economy Lab, or UCL CircEL, acting as a hub for various CE initiatives across UCL. Various activities were associated with the group, a major one being a large research grant based on circular construction minerals, led by Prof. Stegemann (ICEC-MCM 2018). Activities with UCL Estates Sustainability have also led to PhD projects, UKRI-funded projects and urban-scale ones, all related to circularity.

Circulars – Collaborating with TU Delft

To enhance its outreach and foster collaboration, the LCA-CE group has joined the Circulars initiative – a partnership between UCL and TU Delft. The Circulars initiative aims to strengthen ties between the two institutions, with a specific focus on CE within the built environment, regenerative circular urban systems, and the policy and governance of circular systems. Founded by Prof. Joanna Williams, a leading expert in Sustainable Development at The Bartlett School of Planning, Circulars plays a pivotal role in advancing research in these areas. As part of its involvement, the LCA-CE group has actively participated in and delivered seminars on various themes related to CE and engaged in collaborative efforts at both UCL and TU Delft.

2. Research Challenges

The LCA-CE group has set an aim to establish itself as a research hotbed for LCA & CE in the built environment. As such, the team has mapped out an outline of the research domain and aimed to identify a series of current and future research gaps, challenges and activities. Through this work, the team is hoping to identify areas where it can contribute to knowledge, support policy makers and stakeholders, and make a meaningful impact on sustainable building design. The group has categorised challenges and opportunities into three themes (Figure 5): those related to tools and technical aspects, advanced methods and physical elements.

Factors that might impact LCA-CE in the future

Tools / Technical factors

- AI / Machine learning
- EPD & Material passports
- Weatherfile predictions

Methods

- Holistic & complete LCA methods
- Dynamic LCA
- Indicators other than carbon (biodiversity / health / others)
- Urban or national-scale LCA

Physical factors

- 3D print of buildings
- Future climate
- Recyclability / circularity
- Procurement
- Efficient manufacturing processes
- Decarbonisation of the grid

Figure 5. Impact on LCA & CE research in the future

2.1 Tools and technologies

New developments of research tools could transform the way research is done in the built environment. In the research of the LCA-CE group, these could lead to transformations in the way research is conducted and bring to a more meaningful impact on industry and practice.

Within this category, the group has identified key areas that assist in providing more accurate or research outputs or enable a wider look at LCA & CE-related issues. For example, artificial intelligence and machine learning (AI & ML) support our researchers in conducting modelling and simulations more effectively. AI can be trained to predict the behaviour of building systems and provide a quicker, less resourceful set of outputs. AI can also support in automating data analysis, identifying patterns and trends, and optimising resource allocation and decision-making processes.

Other examples in the category of tools and technology include more accurate weatherfile predictions, which would enhance simulation outputs and the robustness of the research, and EPD and material passports, which are predicted to improve the accuracy of modelling and reduce the impact of a potential 'embodied carbon performance gap'.

Experience with past projects in developing novel tools (e.g. H\B:ERT – the BIM embodied carbon calculator developed by IEDE staff) has already shown the potential in merging academic expertise and technical capabilities with practical needs and insights from the industry.

2.2 Methods and frameworks

Another advancement that could make a significant contribution to LCA & CE research is newly employed methods and future LCA & CE frameworks. These mean both generic research methods (that are used in research in general) and specific ones that are specifically used around LCA & CE. For example, while current LCA frameworks are focused primarily on research into CO2, it could be essential to adopt a wider outlook on environmental performance – assuming that carbon emissions will be significantly reduced in the future. Weighing the balance between mitigating carbon emissions and the potential implications on other indicators (e.g. public health, land use and biodiversity) might be an important focus for policy and decision makers.

Similarly, while processes in the lifecycle of the built environment are dynamic in nature (e.g. changes in fuel mix in the generation of energy, heating climates over the years), current research is still mostly static. For LCA & CE research to have a comprehensive set of outputs, dynamic LCA techniques should be employed and used.

Other methods and frameworks which might be used in future research could be a large-scale LCA carried out at an urban level (potentially making use of advanced techniques modelling and simulation techniques, such as AI & ML), or the application of blockchain technology to ensure transparency and traceability across the supply chains and support circularity principles.

2.3 Physical systems: Production, infrastructure and environment

The production processes of construction elements are the primary cause of embodied emissions. Technological improvements in manufacturing processes could bring about a reduction in embodied impacts. For instance, 3D printing has the potential to significantly reduce the embodied carbon of some construction components (Khan, Muammer Koç & Al-Ghamdi 2021). The use of 3D printers on a building scale – that is, those that can print walls on site – could also reduce emissions related to construction actions on site. Such technologies are yet to be researched, as their full potential has not yet been put to test.

On the other side of production processes lies the recyclability and circularity potential of building components. Techniques such as Design for Deconstruction and other circular-minded technologies could have an important role in mitigating lifecycle emissions.

Other areas related to physical systems could evolve around efficient procurement and documentation, which could minimise waste and the reliability of reporting on embodied carbon or the decarbonisation of the grid, which could significantly reduce both the operational emissions in buildings and emissions relating to the production of construction materials.

The physical environment could also affect lifecycle impacts in buildings: future climate scenarios and global warming predictions are the first thing that come to mind when thinking of the impact of the physical environment on LCA & CE. However, the predictions of population decline in many countries, on the one hand, and economic growth in developing countries and increased urbanisation trends, on the other hand, need to be carefully looked at and thought about when focusing on the impact LCA & CE might have on emissions arising from the built environment.

3. Setting the Research Agenda

Following the growing interest in research on LCA & CE in the built environment, the IEDE LCA-CE group aims to establish itself as a resourceful research hub. To achieve this, the team leverages the multidisciplinary nature of IEDE, drawing on a diverse array of expertise across various domains related to LCA & CE. These areas of expertise can be broadly categorised into methodological and thematic fields, which together form a robust foundation for innovative research and practical applications.

3.1 Methodological expertise

Advanced computational skills: Vase research has been done at IEDE using a range of computational methods. AI is used to explore the UK housing stock (Taylor et al. 2019). Generative design systems and optimisation methods were used for investigating lifecycle carbon and cost performance (Schwartz, Raslan & Mumovic 2016; Alasmar, Schwartz & Burman 2023). Digital twin as an approach that can help to more accurately document building components is increasingly used (Mavrokapnidis et al. 2021).

Systems thinking: This holistic approach allows researchers to investigate processes and identify points where interventions can improve sustainability. IEDE has a solid systems-thinking team that was involved in several LCA & CE projects – for example, a project by the Ellen MacArthur Foundation (Macarthur 2010) which applied systems thinking and LCA by promoting the reuse of building materials and the design of buildings for disassembly and reuse. The 'CIRC4Life' project is another example, which focused on developing new CE business models, applying systems thinking and LCA to products' entire lifecycles (CIRC4Life 2018).

Modelling and simulations: Essential for predicting long-term impacts, these tools allow researchers to evaluate different scenarios and their potential environmental impacts. IEDE has made use of thermal simulations in many projects, including the Modelling Platform for Schools and DREAMS – thermal stock models of school buildings in England (Schwartz et al. 2022; Raslan & Davies 2010).

3.2 Thematic expertise

LCA and CE: Core to the group's research, LCA & CE principles guide the assessment and improvement of environmental performance across sectors. This involves evaluating the full lifecycle impacts of products and systems, from raw material extraction to end-of-life disposal. Expertise in LCA and CE ensures comprehensive strategies for reducing environmental impacts and promoting sustainability.

Energy efficiency: A critical factor in LCA & CE, the group's expertise includes developing and employing passive and active environmental design strategies that reduce energy demand and use in buildings.

Resource efficiency: Focusing on efficient use of materials and resources, this area includes strategies for reducing material use, circularity, promoting recycling, and designing products for longevity and ease of disassembly.

Having mapped the research potentials and challenges, the group is now focusing on harnessing existing multidisciplinary skills while developing new ones and bringing in external expertise whenever needed. Using multidisciplinary teams effectively can result not only in novel and unique solutions for existing problems, but also in the formation and identification of original and complex new ones.

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Expert workshops: Reflections and future research pathways

As part of the 60 years of IEDE celebrations, the LCA-CE group has organised an international workshop to identify the main research paths in the future, set up the agenda for research ideas and establish collaborations within the international community of scholars. Table 1 presents the participants joined from leading universities and institutes around the world.

The workshop started with a short discussion using systems thinking and a causal loop diagram (CLD), mapping the main processes in LCA & CE and setting up the basis for the discussion on updating the diagram and expanding on to future developments and their impact on research in the field.

The CLD depicted in Figure 6 was developed by the IEDE LCA-CE team and presented to workshop participants. The diagram was framed by two boundary processes: Building Design & Operation and Life Cycle Carbon Footprint. Following the EN 15978 protocol, the CLD outlined three primary phases: construction materials (upfront impacts), energy consumption (operational performance) and end-of-life/recyclable emissions. Sub-processes and their interconnections were mapped, illustrating both positive and negative effects on a building's overall carbon footprint. This diagram provided a foundation for workshop discussions, during which participants were invited to suggest additional factors and relationships to incorporate.

Table 1. Expert workshop participants

Name	Affiliation
Reham Alasmar	PhD Researcher, UCL
Benjamin Sanchez Andrade	Assistant Prof., Appalachian State University
Rahman Azari	Associate Prof., Penn State University
Carlo Schmid	PhD Researcher, ETH Zurich
Manish K. Dixit	Associate Prof., Texas A&M University
Edwin Zea Escamilla	Senior Researcher, ETH Zurich
Thaleia Konstantinou	Associate Prof., TU Delft
Marios Kordilas	PhD Researcher, UCL
Matt Roberts	Postdoctoral researcher, Berkley
Charlotte Roux	Lecturer and Researcher, Paris School of Urban Engineering and Ecole des Ponts Paristech
Yair Schwartz	Lecturer, UCL
Simon Vakeva-Baird	PhD Researcher, UCL
Dong Yahong	Associate Prof., Macau University of Science and Technology

This diagram provided a foundation for workshop discussions, during which participants were invited to suggest additional factors and relationships to incorporate. Participants explored new concepts and connections, to develop a more holistic understanding of the building's carbon footprint. Key points included:

- **Energy production:** A suggestion was made to include renewable energy sources (e.g. photovoltaic panels) and account for their circular economy implications, such as resource use and production processes.
- **User behaviour and stakeholders:** Emphasis was placed on including user behaviour and stakeholder roles, acknowledging how active and informed decision-making affected the environmental impact of projects.
- **Construction materials:** The significance of emerging bio-based materials and biogenic carbon sequestration was also discussed. Environmentally efficient construction materials (bio-based) could cut upfront emissions, and advanced construction techniques could transform the way buildings function, bringing construction emissions down.
- **The impact of extreme weather events** on material replacement and refurbishment needs was also mentioned as an important issue. Recent examples of severe weather events, such as hurricanes and floods, required entire areas to be re-built.
- **Integration of circular economy:** It was emphasised that circular economy practices are intrinsic to LCA rather than separate processes. It is essential to establish a methodological connection between the lifecycle of materials and buildings.
- **Higher-order circularity:** A suggestion was made to incorporate a higher order of circularity, like reducing and rethinking resource use, including more efficient use of space and shared facilities.

On discussing future research pathways, focusing on tools and technical factors, methods and physical factors, key points included:

- **AI & ML:** Participants recognised AI & ML as powerful tools for enhancing data analysis, modelling and simulation. It was noted that AI has the potential to simplify decision-making for design teams by breaking down complex data into actionable insights.
- **Internet of Things (IoT):** The role of IoT in improving data traceability was pointed out, as well as real-time monitoring, which could support LCA & CE practices.
- **Digital twins and BIM:** The importance of digital twins and BIM in capturing the dynamic nature of buildings and their environments was mentioned. It was suggested that these technologies could provide more accurate data for lifecycle assessments.
- **Data quality and accessibility:** Some concerns were raised about the variability and quality of EPDs. The development of simplified LCA methods to facilitate decision-making was suggested as an example of critical evaluation of inaccurate published EPD data.
- **Dynamic and prospective LCA:** Participants stressed the need for future research to account for dynamic and prospective LCA methods that consider future changes in manufacturing processes, energy mixes and environmental impacts.
- **Holistic and absolute LCA:** Participants discussed the importance of holistic approaches that encompass broader environmental and societal impacts. The role of urban planning and policy in influencing circular economy practices was raised.

The workshop highlighted several critical insights for future research on and implementation of LCA & CE. A key takeaway was the integration of emerging technologies like AI, IoT and digital twins, which can significantly enhance LCA and CE analyses through more accurate and dynamic assessments.

Participants emphasised the importance of data quality and accessibility. Reliable, high-quality data is essential for effective LCA & CE practices, and there was a call for improved data collection, standardisation and sharing practices to ensure robust analyses.

The workshop also underscored the need for holistic and dynamic LCA methods. There is a growing recognition that assessments must consider future changes and broader environmental impacts, calling for methodologies that are both comprehensive and adaptable.

Stakeholder engagement and supportive policy frameworks were identified as crucial. Effective stakeholder engagement, along with clear definitions and policies, is necessary to advance LCA & CE research and implementation. Involving all relevant parties and establishing conducive policies can drive progress.

Furthermore, discussions highlighted the importance of integrating higher-order circularity measures into LCA practices. This includes reducing and rethinking resource use, alongside traditional recycling and reuse strategies, and considering how space is utilised in these practices for a more comprehensive approach.

The workshop emphasised the significance of interdisciplinary collaboration and innovative research methods in addressing the challenges and opportunities within LCA & CE. Moving forward, efforts from various disciplines and the adoption of cutting-edge technologies will be essential to progress in these fields and to achieving sustainability goals.

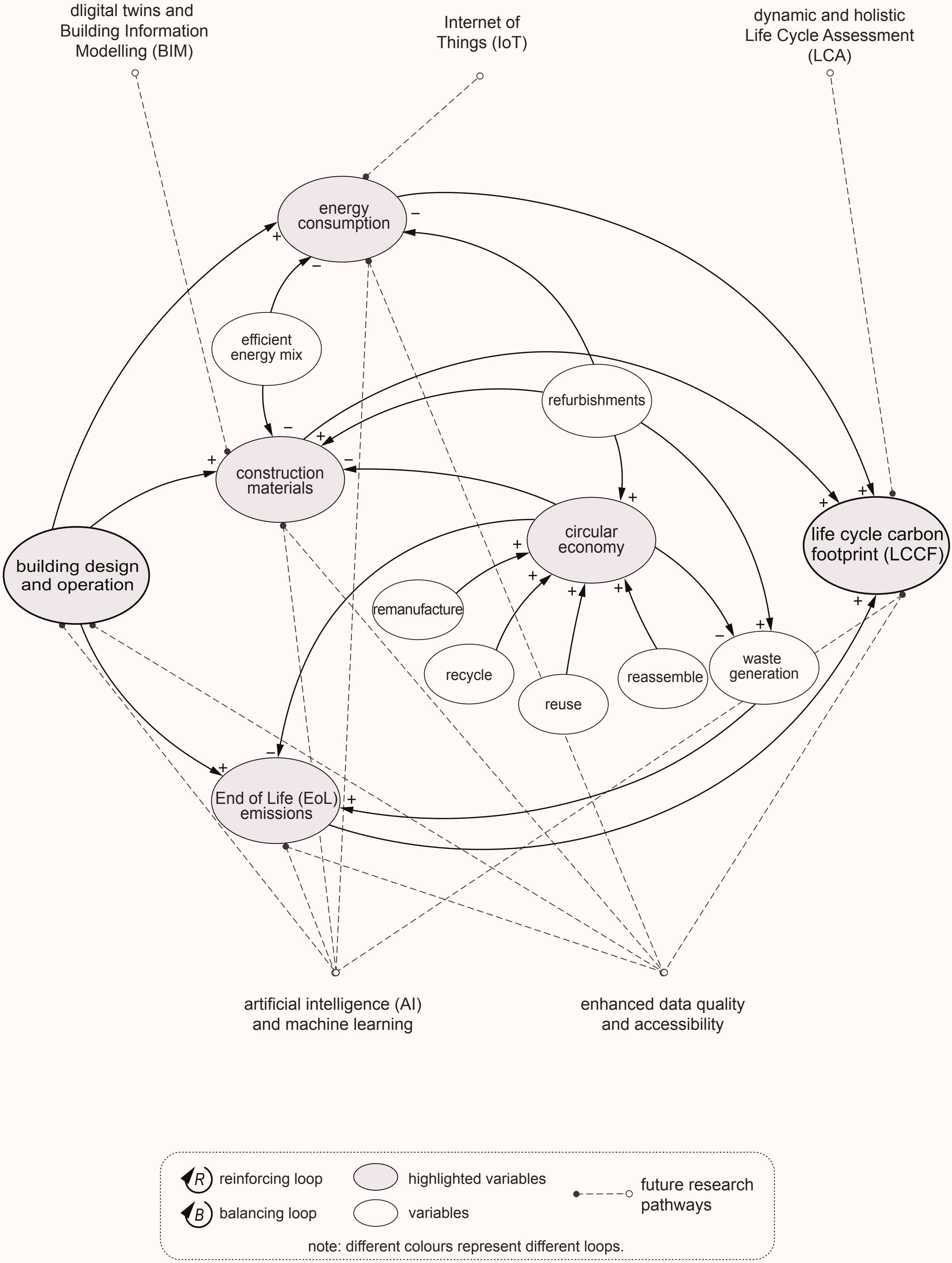

Figure 6. Causal loop diagram: Life cycle assessment and circular economy (Image credit: Yuhong Wang & Daijia Ke 2024)

THEME: ENERGY USE, RETROFIT AND NET ZERO CARBON

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1. Where We Are

Achieving net zero carbon emissions represents a key climate change mitigation target first enshrined in law by the UK in 2019 and subsequently adopted by several countries (HM Government 2019; Our World in Data 2024). Meeting this target requires actions across several sectors, including the built environment, which is responsible for 26% of greenhouse gas (GHG) emissions globally (IEA 2023). To reduce building sector emissions, we must tackle both the carbon associated with operational energy use and the embodied emissions linked to construction material and building technologies. These are considerations for both new buildings, which can be designed to a high level of energy efficiency, and existing buildings, which may not be future-fit in their present state.

The UCL Institute for Environmental Design and Engineering (IEDE) is at the forefront of research in energy use, retrofitting and the transition to net zero buildings. Our research delves into the energy consumption and carbon footprint of existing buildings, providing insights into their performance and potential for improvement. Recognising the critical role of retrofitting, IEDE has led cutting-edge research on the effectiveness of energy efficiency measures, their co-benefits and unintended consequences as well as the crucial emerging area investigating the inter-relationships between adaptation and mitigation. By integrating its world-leading research into its teaching, IEDE is cultivating a new generation equipped to lead in the creation of low-carbon and sustainable built environments.

1.1 Pathways and challenges to achieving net zero

IEDE research is underpinned by our recognition of the many pathways and challenges to achieving net zero. Our work has shaped the research agenda in this field, set the benchmark for industry and professional best practice, delivered real-world impact, and significantly influenced the formulation of national and international policies.

Recognising and designing for future uncertainties
Achieving the net zero target in a cost-effective way requires careful consideration of the local context of the building stock and climate, differing and evolving occupants' needs, and uncertainties relating to how these may be embedded in the future. In recognising the need to formulate immediate plans and actions where uncertainty is impactful yet irreducible, IEDE is leading the way in developing robust design approaches to inform uncertainty-based decision-making within key areas such as future thermal comfort. These approaches can facilitate the analysis and identification of climate change response actions that are less sensitive to uncertainty yet expected to maintain the intended performance levels (Cui et al. 2022).

Complex-to-decarbonise (CTD) homes represent a further key area of uncertainty within the net zero agenda. Despite increased policy interest, relatively little is known about CTD homes, which are those with either one, or a combination of, physical, locational, demographic or behavioural attributes that prevent effective decarbonisation. System-level financial, economic and organisational factors further complicate these issues. Building on our research to understand the decarbonisation potential of CTD homes, our work in this area has enabled the first step to addressing this challenge by developing a novel scalable framework for the identification and spatial mapping (Figure 1) of the dwelling-by-dwelling distribution of CTD homes across UK nations (Cui et al. 2024).

The impact and opportunities in future technologies
IEDE researchers have developed a methodology to optimise indoor air quality using technologies such as HVAC systems, ensuring that building retrofits – while improving airtightness – do not negatively impact occupant health. This approach has underpinned the formulation of reuse strategies for office and commercial buildings in Egypt (Hamada, Raslan & Mumovic 2021). Our methodology involves the simultaneous simulation and control of multiple air contaminants (Hamada, Hong & Raslan 2023), accounting for filter pressure drops and bypass. We also evaluated various ventilation scenarios, including natural, mechanical and recirculation, using monitored air data from real case studies (Hamada et al. 2023). This comprehensive approach ensures that retrofitted buildings maintain healthy indoor environments without compromising on air quality.

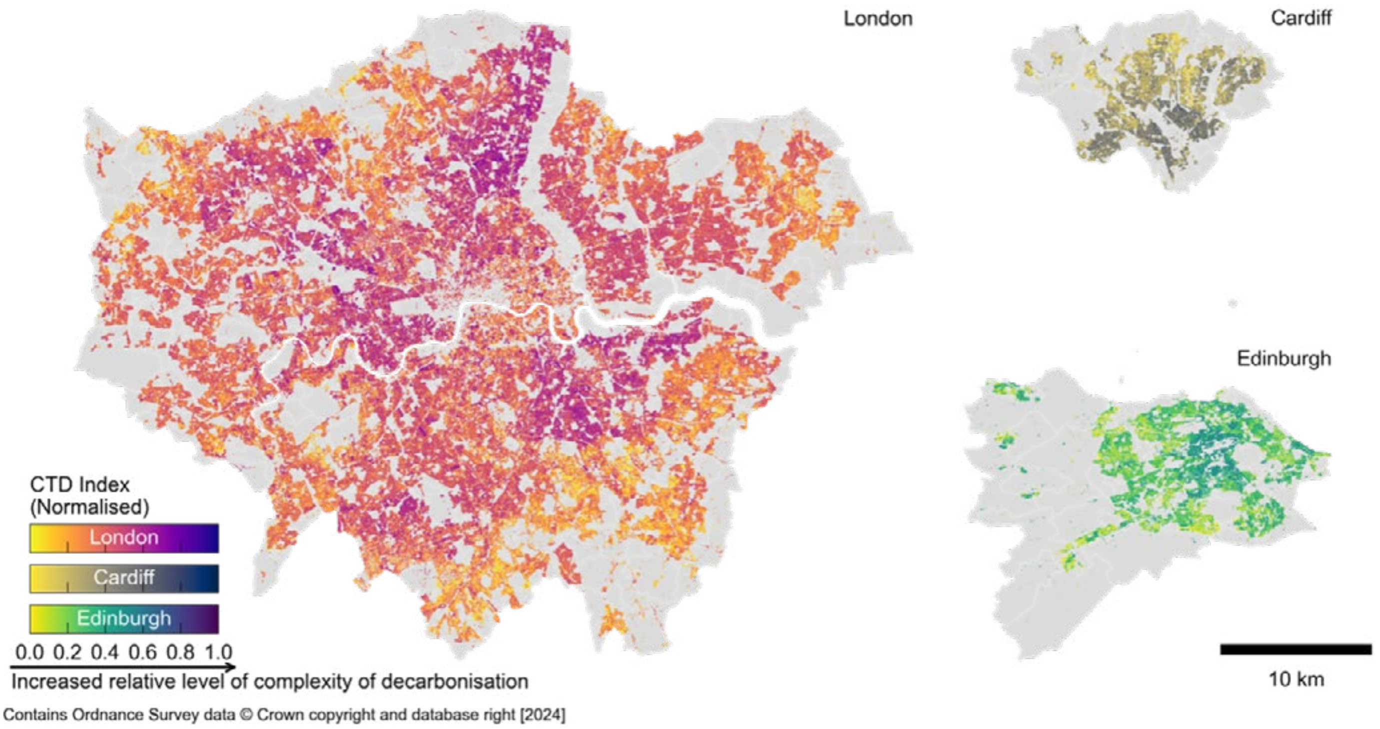

Figure 1. Complex-to-decarbonise index maps highlighting the level of complexity of decarbonisation for homes across UK cities. Darker areas indicate areas with a higher concentration of CTD homes (Image credit: Cheng Cui, 2024)

Under the Department for Energy Security and Net Zero (DESNZ) Climate Services for a Net Zero Resilient World programme, IEDE has been at the forefront of quantifying the impact of climate change on the future heating and cooling needs of the UK housing stock, with a particular focus on vulnerable populations. By modelling a range of climate change projections (UKCP18) and their effects on thermal comfort and heating and cooling loads, we evaluated the implications for different climate-vulnerable groups (Ferguson et al. 2023). Collaborating with key stakeholders, we identified low-cost, low-carbon 'win-win' measures that minimise the adverse societal and environmental impacts of climate change-induced changes. Future work will focus on additional retrofit interventions and technologies, such as the uptake of heat pumps for both heating and cooling.

Given the role of heat pumps in achieving net zero ambitions, our research has explored how domestic heat pump performance can be improved through quality installation and appropriate control facilitated by behaviour change (Oikonomou 2022; Oikonomou et al. 2022). Using a systems-thinking framework, IEDE researchers analysed sociotechnical data from 21 case studies, identifying processes that enable well-performing heat pumps. This analysis highlighted four leverage points: comprehensive training for technicians, simplified educational and feedback mechanisms, revised installation regulations and the integration of smart controls.

Informing the 'retrofit or demolish' debate

Retrofitting our existing housing stock is crucial for urban regeneration programmes. Studies highlight the significant impact of construction on carbon emissions and biodiversity loss, showing that current housing strategies could consume England's entire carbon budget for maintaining a 1.5°C limit by 2050 (Zu Ermgassen et al. 2022). Within this context, exploring the feasibility of redistributing resources towards retrofitting, maintenance and repair of underoccupied and underused housing stock holds great potential (Pagani et al. 2024).

As buildings age, retrofitting offers an alternative to demolition by extending their lifespan, potentially minimising environmental impact, limiting community disruption, and preserving housing stock and cultural heritage. The debate between retrofitting and demolition involves various dimensions, including environmental, economic, social and regulatory factors (Power 2008).

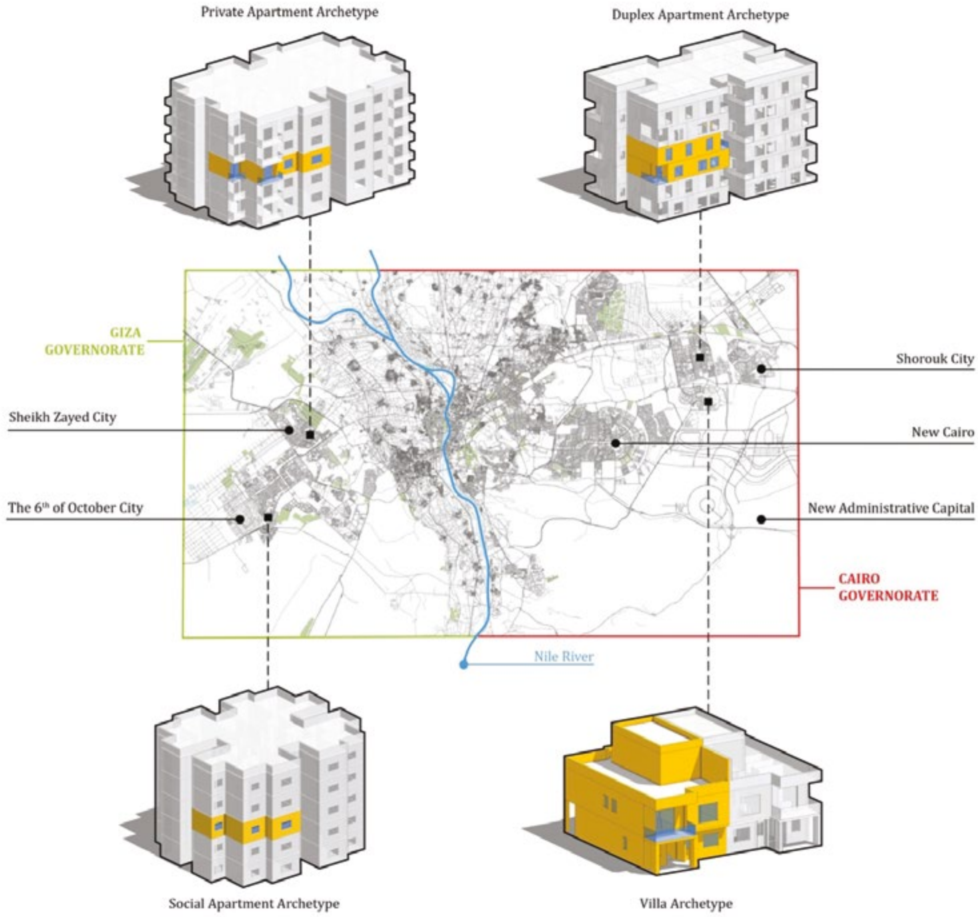

Figure 2. Housing archetypes developed for lifecycle assessment in the context of new cities in Egypt (Image credit: Fady Abdelaziz 2023)

Our research has made significant contributions to this debate by developing methodologies to evaluate the environmental impact and economic viability of retrofitting versus demolition and new construction (Schwartz et al. 2022). Aligned with IEDE's Life Cycle Assessment and Circular Economy Research Theme (see Chapter 1.7), these methodologies incorporate approaches such as lifecycle analysis and lifecycle cost analysis across a range of national and international contexts (Figure 2). This includes examining the initial investments, operational savings, potential revenue from improved property values, carbon footprints, energy consumption and resource use associated with both approaches (Abdelaziz, Raslan & Symonds 2021, 2023; Hamada, Raslan & Mumovic 2021; Hamada, Raslan & Hong 2023).

To inform policies that encourage the adaptive reuse of buildings, a current IEDE study on permitted development housing aims to understand the health and wellbeing impacts on residents in buildings converted from commercial use, such as offices that have been repurposed into flats (Pineo et al. 2024). This research will inform wider policy debates about whether deregulating urban planning supports healthier living environments and how best to manage and govern the development of such conversions in the future.

The Total Operational Performance project

While the concept of the 'performance gap' in building energy performance is well established, and useful work to understand this issue has been undertaken, potential unintended consequences related to the interlinked issues of energy/indoor environmental quality (IEQ) present an even more complex challenge (Jain et al. 2020). The Total Operational Performance collaborative project between IEDE and Tsinghua University investigated the problem of the performance gap in energy performance and IEQ in schools, offices, hospitals and residential blocks in the UK and China. This led to the publication of the Chartered Institution of Building Services Engineers (CIBSE) Technical Memoranda 61–64 and contributions to the International Energy Agency Energy in Buildings and Communities (IEA-EBC) Programme Annex 68 (CIBSE 2020a–d).

Haringey PassivTerrace
As part of the groundbreaking Retrofit for the Future project, a deep retrofit of a Victorian terrace house aimed to reduce energy use and carbon emissions by 80% (Metropolitan Housing Partnership 2011). IEDE was part of the delivery team for this house, owned by the Metropolitan Housing Association. Originally two flats, the house was converted back into a single-family home and has been continuously occupied by the same tenant. The initial design included super-insulation and airtightness measures, complemented by mechanical ventilation with heat recovery. IEDE contributed to a revisit of the retrofit assessing its performance over 12 years, which highlighted that, while the thermal performance of the building fabric has not significantly deteriorated, the unusual HVAC equipment is proving difficult to maintain and may need to be replaced (Godefroy & Baeli 2014).

Informing the Climate Change Committee (CCC) advice on the UK's long-term targets
IEDE academics have worked on the first in-depth analysis to holistically study the UK's CTD homes from a sectoral perspective, quantifying their significant decarbonisation potential to underpin the CCC net zero advice to the UK Government. The study assumed widespread acceptance and effective performance of existing and emerging decarbonisation technologies. It highlighted the value of achieving a zero carbon future for CTD homes and identified key knowledge gaps affecting our understanding and ability to decarbonise these homes effectively (Foster et al. 2019).

1.2 The co-benefits and unintended consequences of energy use, retrofit and net zero carbon transition

While the motivation behind the net zero transition is to limit the increase in global temperature and its associated consequences, it is becoming increasingly clear that measures taken to curb GHG emissions offer additional benefits (co-benefits). Past and ongoing IEDE research has played a pivotal role in identifying co-benefits and quantifying their impact. For example, our work revealed that improved home insulation and airtightness, when accompanied by appropriate ventilation levels, resulted in health benefits (2,241 quality-adjusted life years per 10,000 persons over 50 years) due to a reduction of indoor exposure to air pollution and the improvement of winter-time indoor temperature (Hamilton et al. 2015).

In addition to the co-benefits of energy efficiency, IEDE has extensively studied the unintended consequences that improved insulation, and airtightness can have when poorly installed or without consideration for other building characteristics. In the absence of adequate ventilation or shading, improved airtightness and insulation can exacerbate indoor overheating and the risk of heat-related mortality (Taylor et al. 2018a, 2018b). Another unintended consequence is the accumulation of pollutants of indoor origin, including radon, an inert radioactive gas that seeps into properties through the ground and is a major cause of lung cancer. IEDE-led research revealed that energy efficiency measures that increase the airtightness of homes have an adverse association with indoor radon levels (Symonds et al. 2019).

The following past and ongoing IEDE research has explored the co-benefits and unintended consequences of retrofit and net zero.

Policy and Implementation for Climate and Health Equity
Policy and Implementation for Climate and Health Equity (PAICE) is a Wellcome Trust funded project that seeks to inform UK climate-related policy making. As a collaboration between IEDE, the London School of Hygiene and Tropical Medicine, the CCC and the Greater London Authority, PAICE takes a transdisciplinary approach to identifying shared objectives centred on the impacts of climate change mitigation actions on health and health equity across the housing, energy, food and transport sectors. In doing so, PAICE aims to improve the CCC's ability to monitor and advise on climate change action by enhancing existing frameworks, incorporating the consideration of health equity and adapting national frameworks for local application (UCL 2024).

Health Protection Research Units
The National Institute for Health and Care Research's Health Protection Research Units (NIHR-HPRUs) are partnerships between universities and the UK Health Security Agency (UKHSA). IEDE has participated in two impactful HPRUs, most recently the research unit on Environmental Change and Health. Through this collaboration, we have contributed to significant research on the link between climate change mitigation, adaptation and health, including: a position paper on the potential

impacts on indoor air quality and health from the net zero transition published in The BMJ (Petrou et al. 2022); the net zero chapter in UKHSA's flagship publication, Health Effects of Climate Change (Macintyre, Cordiner & Israelsson 2023); and a white paper on 'Refurbishment for Net Zero' (BSRIA 2023).

1.3 Working with stakeholders

In a warming climate, a successful net zero transition will be influenced by societal factors as much as technical ones. For our built environment it will entail balancing technical performance with IEQ. Existing literature on retrofit emphasises the importance of collaborating with a range of stakeholders to understand their roles, priorities and motivations to aid the development of effective retrofit value propositions. Within this context, occupants play a critical role in determining the types and impacts of retrofit solutions, with emerging research suggesting that engaging with occupants can offer input into sociotechnical innovation, paving the way for novel net zero retrofit approaches.

At IEDE, we use participatory approaches to incorporate stakeholder and occupant perspectives, values and expertise in formulating retrofit strategies and designing and assessing net zero buildings, especially when conflicting objectives are present. Our research has adopted and innovated diverse methods of engagement and participatory platforms, highlighting the value of these approaches in creating effective and sustainable decarbonisation strategies.

Mental models around demolition versus retrofit in social housing regeneration
Regeneration of social housing can be motivated by health and sustainability narratives whose outcomes can differ profoundly. Using participatory system dynamics, we explored the mental models of a range of stakeholders in the sector (Pagani et al. 2024). The resulting causal loop diagrams display the system structures underpinning decisions to demolish and densify rather than retrofit.

Stakeholder-led hospital building refurbishment
The design of hospital buildings is driven by the high energy demands required to meet both service requirements and occupant needs. The UK National Health Service (NHS) has been diligently tracking its carbon footprint and continually enhancing its strategies to meet net zero commitments, which remains a substantial challenge (NHS England & NHS Improvement 2020). In response to this, we are developing a comprehensive framework which integrates stakeholder preferences and priorities, enhancing their decision-making capabilities in low-carbon refurbishment strategies (Doguc, Aparisi & Raslan 2024).

Supporting net zero building design through multi-criteria decision-making methods
Multi-criteria decision-making (MCDM) methods incorporate a wide range of building performance criteria beyond energy and carbon objectives, especially in the early design stages. Our research has applied MCDM methods to three climatically and contextually distinct non-domestic building projects through participatory workshops that leveraged the experiential and contextual knowledge of design teams (Vakeva-Baird et al. 2023). This work revealed that design and client-side stakeholders prioritise healthy environments over carbon targets, financial feasibility and social outcomes, demonstrating the need to integrate these factors early in the design stages to align objectives and achieve performance.

Stakeholder collaboration for advancing Life Cycle Assessment (LCA) and circular economy (CE) principles
Incorporating LCA & CE principles in the early-stage building design enables a comprehensive evaluation of environmental impacts associated with the building and supports decarbonisation. Our research, adopting a co-production approach to engage stakeholders, identifies key requirements for advancing LCA & CE implementation (Atik, Aparisi & Raslan 2024). Key mechanisms include legislative support, stakeholder engagement, skills development and effective communication frameworks, which are essential for developing future strategies, such as a BIM protocol for integrating LCA & CE in building design.

2. Research Challenges

Our work across the Research Theme on Energy Use, Retrofit and Net Zero Carbon has identified the following emergent key research challenges.

Energy flexibility
Decarbonising electricity grids and the electrification of building services are crucial for achieving net zero carbon performance in buildings. Consequently, there is a growing emphasis on energy flexibility and demand-side management to match grid capacity with building demand. This focus is demonstrated by the European Smart Readiness Indicator and the UK's Smart Building Rating scheme. Energy flexibility is a key research area in the Energy Resilience and the Built Environment Centre for Doctoral Training, where IEDE academics supervise multiple projects to optimise energy use and enhance grid resilience (UCL 2019).

Future-fit and inclusive retrofit
In an evolving world, evidence-based research is essential to ensure building upgrades meet current and future targets. Strategies must consider the inter-relationships between mitigation and adaptation goals and respond to the projected evolution of building stock and occupants (Raslan & Ambrose 2022). Additionally, this future-proofing agenda should address the retrofit of challenging and under-researched segments, such as CTD stock and hard-to-reach energy users. New optimised decision-making approaches, developed with key stakeholders, should emphasise decarbonisation as a pathway to adaptation and climate equity.

Future technologies
Underexplored technologies such as shallow geothermal energy systems and thermal energy storage technologies may support the broader decarbonisation efforts in the heating and cooling sector. The reliability and continuous operation could prove valuable for balancing the intermittent nature of renewable sources (Blum et al. 2023; Kanna I 2024; Kiruja & Barrera 2022).

The building performance–systems approach–stakeholder nexus
The potential of systems approaches to study the unintended consequences and co-benefits of net zero and decarbonisation policies for health and wellbeing has been shown to be promising (Eker et al. 2018; Macmillan et al. 2016; Pagani et al. 2023). There is also a key challenge in integrating building performance simulation with multi-criteria decision analysis and a need to develop and test methodological tools that support such engagement and achieve these benefits (Ohene, Chan & Darko 2022).

3. Setting the Research Agenda

Our work has underscored the necessity of a multifaceted, interdisciplinary and forward-thinking approach to support the achievement of net zero ambitions. As we set the future research agenda for the IEDE Research Theme on Energy Use, Retrofit and Net Zero Carbon, it is essential to strengthen and build on our established expertise in the diverse areas mentioned above. Additionally, we must evolve and expand our work to address the increasing recognition of the importance of designing for uncertainty and understanding the relationship between adaptation and mitigation in our built environment.

In refining this focus, and building on discussions from our Research Theme's international expert workshop (see Box 1 for details), the following emergent themes underpin our future research agenda:

1. Optimising retrofit for a changing climate and evolving occupant needs
2. Understanding the role, impact and consequences of future retrofit technologies
3. Ensuring a stakeholder-led, future-fit and inclusive retrofit

Specific research agenda topics are as follows:

Integrating uncertainty into impact models of mitigation and adaptation strategies using robust design and multi-objective analysis approaches to guide more informed and inclusive decision-making.

Exploring the use of deep learning-based neural network models to address the high dimensionality of inputs in impact models.

Expanding research to include under-researched and international contexts, ensuring the inclusiveness and resilience of retrofit strategies and the broader net zero transition.

Optimising technology performance through retrofits, which is critical for the effective operation of heat pumps and the reduction of peak demands for both heating and cooling.

Maximising energy flexibility through the implementation of retrofit measures that reduce peak heating/cooling demand, improve thermal inertia and maximise opportunities for integrating heat storage solutions.

Developing and implementing low-impact solutions on the electricity grid to minimise the consequences of technologies like heat pumps.

Exploring the potential of new technologies such as underground thermal energy storage that may support the net zero transition.

Advancing the understanding and modelling of occupant behaviour in building stock models, where representation of occupants and their interactions with building environmental control systems remains a challenge.

Enhancing stakeholder engagement and cross-learning through novel frameworks and approaches to support all the above activities across this Research Theme.

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Expert workshops: Reflections and future research pathways

The Energy Use, Retrofit and Net Zero Carbon Research Theme international expert workshop focused on addressing the key question: “How can built environment Net Zero ambitions better integrate with key adaptation priorities?”

The workshop concentrated specifically on adaptation to the increasing risks posed by indoor overheating. Collaborating with a group of world-leading experts from diverse international institutions and disciplines (Table 1), we co-developed a CLD that highlights the main research areas and gaps related to our research question (Figure 3).

The development of the CLD was underpinned by discussions on a diverse array of topics, showcasing the multifaceted and interdisciplinary viewpoints of researchers, practitioners and policy makers involved in tackling issues of energy use, retrofit and net zero carbon. The CLD revealed a number of factors influencing the integration of net zero ambitions with adaptation to indoor overheating and the presence of balancing and reinforcing loops. Balancing loops describe mechanisms where changes in factors counteract themselves after moving through the loop, helping to stabilise the system. In contrast, reinforcing loops represent dynamics where changes in factors amplify themselves after moving through the loop.

In developing the CLD, a significant focus was on the rollout of heat pumps as part of low-carbon heating upgrades, a key measure required to achieve net zero ambitions and address future adaptation needs. This transition is expected to significantly affect electricity grids. Challenges such as space constraints and limitations associated with microbore pipework, which may hinder optimal heat transfer, are critical. Additionally, a primary challenge in installing heat pumps in UK homes is the capacity of district network operators and local electricity grids.

Table 1. Expert workshop participants

Name	Affiliation
Shady Attia	University of Liege, Belgium
Rory Bergin	HTA Design London, UK
Nick Eyre	University of Oxford, UK
Hodeis Farkhondeh	HTA Design London, UK
Zoe De Grussa	Chartered Institute of Building Services Engineers, UK
Mohamed Hamdy	Norwegian University of Science and Technology, Norway
André Paul Neto-Bradley	Department for Energy Security and Net Zero, UK
Brian Norton	University College Cork, Ireland
Marylis Ramos	Savills UK
Dave Roberts	National Renewable Energy Lab, USA
Marina Topouzi	University of Oxford, UK
Iain Walker	Lawrence Berkeley National Laboratory, USA

Currently, peaks in electricity and heating demand occur on separate systems (the electricity grid and the gas grid, respectively). A future shift towards heat pumps will concentrate peak heating demand on the electricity grid. Therefore, future research agendas must consider three key aspects to mitigate the risks associated with this shift: reducing peak heat/cooling demand, maximising energy flexibility and developing low-grid-impact solutions.

Optimising retrofit measures is crucial for effective heat pump use, as poorly insulated buildings increase the size and electrical demand of heat pumps. Future research into retrofits should investigate passive fabric energy efficiency measures, improving airtightness, and installing shading to reduce peak demands for both heating and cooling, thus minimising the grid impact of heat pump rollout. Additionally, exploring how energy flexibility can be maximised through retrofit is necessary to identify ways to prevent overloading the electricity grid. This may involve upgrading the building fabric to improve thermal inertia or adding heat storage solutions as part of the retrofit.

An emerging area of knowledge focuses on developing and implementing low-grid-impact solutions. These include sustainable cooling solutions currently being tested through United Nations Development Programme-funded research in North Africa and the Middle East and innovative low-grid-impact ground source heat pumps and charging solutions in the UK and the USA.

As extreme heat episodes increase in frequency and severity, and maximum temperature records are regularly exceeded, urgent action to mitigate the risks posed by heat is required. This is especially important in the context of increasing urbanisation, which exacerbates high ambient temperatures within cities, known as the urban heat island effect. While adaptation efforts have often been considered independently of climate change mitigation actions, our CLD was used to explore synergies and potential overlaps to maximise benefits, minimise costs and unintended consequences, and consider learnings from international contexts such as sustainable cooling.

Measures to improve fabric energy efficiency may reduce the risk of indoor overheating, as seen with loft insulation, but may also exacerbate it if the interaction of factors such as high glazing ratio and increased airtightness is not considered during building retrofit/design stages. Implementing passive measures (including internal/external shading) and ensuring adequate ventilation alongside fabric improvements acts to balance factors that increase overheating risk, resulting in homes that are more resilient to heat and less reliant on heating or air conditioning. This could initially reduce the number of fuel-poor homes struggling to maintain comfortable indoor temperatures. However, many of these homes may be CTD, so that barriers to decarbonisation may also present similar challenges to their adaptation.

Research over the last few decades has provided an understanding of the relationship between indoor temperature exposure and thermal comfort. Research gaps on thermal comfort remain, and it is crucial that these are addressed. Less is known about the relationship between indoor heat exposure, morbidity and mortality. Quantifying these relationships and differences in heat vulnerabilities is essential to ensuring that buildings are future-fit.

In developing our CLD, we identified evolving human needs as a key research area. Technological innovation, along with changes in climate and demographics, is expected to result in human needs differing from when most of our existing buildings were constructed. Designing for the future requires first understanding the underlying trends in evolving human needs and designing buildings that are net zero-ready and resilient to climate change, and that enable their occupants to thrive.

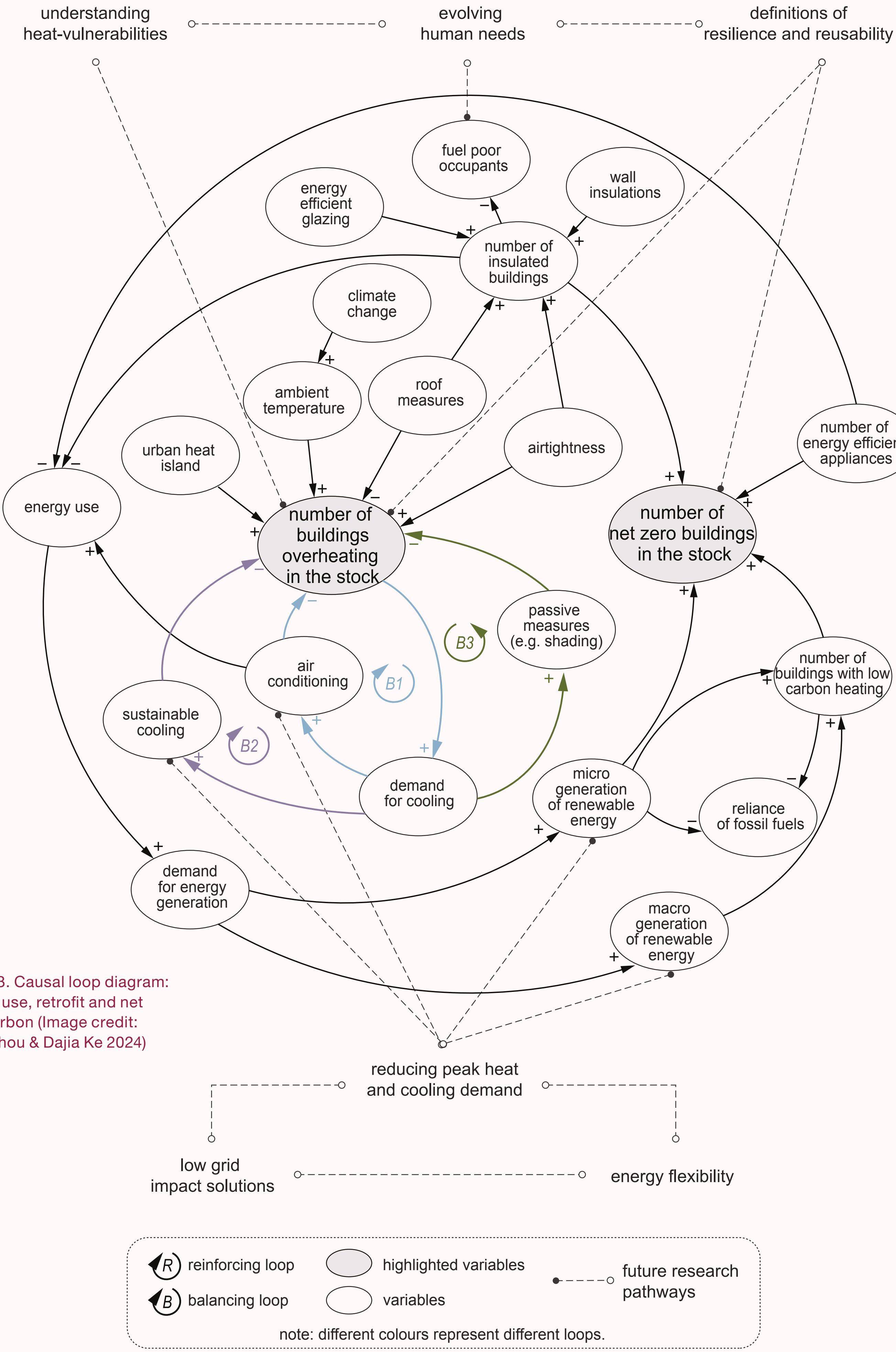

Figure 3. Causal loop diagram: Energy use, retrofit and net zero carbon (Image credit: Koko Zhou & Dajia Ke 2024)

THEME: SYSTEMS THINKING AND TRANSDISCIPLINARITY

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Figure 1. Photo of a workshop activity with the Research Theme's causal loop diagram (Image credit: Oscar Brousse)

1. Where We Are

This chapter presents our collective reflections of applying a transdisciplinary approach and systems thinking on a range of research projects and activities from within the UCL Institute for Environmental Design and Engineering (IEDE). We outline how we have developed innovative methods and practices to bring together and integrate diverse types of knowledge to co-create new knowledge. This experience is shaped by a range of contributors, including other researchers and research partners within projects, students on our programmes, workshop participants (Figure 1) and organisations with whom we have worked in partnership over the years.

A variety of definitions for both 'transdisciplinarity' and 'systems thinking' reveal different aims, perspectives and delivery approaches in theory and practice. To provide a clearer understanding of our work, we begin with some definitions and principles that underpin our approach. The definition of transdisciplinarity that aligns with and informs our work is that proposed by Stokols and colleagues. They describe transdisciplinary research as "… an integrative process whereby scholars and practitioners … work jointly to develop and use novel conceptual and methodological approaches that synthesise and extend discipline-specific perspectives … to yield innovative solutions" (Stokols, Hall & Vogel 2013, p. 6). Furthermore, we define systems thinking as a skill, a way of thinking and approach focusing on interconnections, non-linearities, and understanding patterns of complex system behaviour and synergies.

While transdisciplinarity and systems thinking are distinct approaches, each rooted in its own knowledge base and theoretical frameworks, within IEDE we have identified an overlap between them, based on the shared values that underpin them. Our work is united, and driven, by three common principles:

- An interest in mutual learning and knowledge co-creation. We create and study processes where diverse perspectives and knowledge can come together
- A focus on addressing complex societal challenges. We have a desire to develop strategies to deepen our understanding of, and create innovative solutions to, a range of complex societal problems
- An emphasis on understanding how people's and organisations' experiences, perceptions and decision-making processes shape solutions and outcomes.

1.1 The evolution of our work

In the 1980s and 1990s, much of the work within The Bartlett relied on individual disciplines using existing tools and techniques from their own area of expertise by applying them alongside tools from other fields. In the 2000s, however, IEDE's strategic direction shifted towards a truly multidisciplinary approach. The department was awarded three consecutive EPSRC Platform Grants (2006–2010, 2011–2016 and 2017–2023) to strengthen the links between engineering research and mathematical, physical, chemical and biological sciences, as well as economic and social research. The aim was to stimulate broader scientific discoveries and their applications. Since then, the department has taken a leading role in addressing important international challenges in relation to health, energy and conservation in buildings, through policy, non-government organisations and industry partnerships. The Platform Grants provided sustained resources that enabled a substantial change in the way IEDE undertakes research and collaborates with new disciplines. The first Platform Grant supported the recognition of complexity in the built environment, and the second Platform Grant focused on the unintended consequences arising from this complexity. The third Platform Grant emphasised systems thinking to address such unintended consequences and aimed to transform scientific understanding of the systemic nature of a sustainable built environment, marking a "fundamental departure from business as usual".

Understanding the complexity in the built environment highlighted the need for new ways of working. For example, the low-energy refurbishment of around 400 homes in the north of England has had a 100% failure rate due to disastrous moisture issues, costing millions to rectify (de Selincourt 2018). This had implications for the entire decarbonisation plan, for the health of the building occupants, for the communities involved and for the economic value of these properties. Recognising the built environment as a complex system, research within IEDE shifted to a new multi-, inter- and transdisciplinary systems-thinking approach. The new systems thinking process was piloted in the Housing, Energy and Wellbeing (HEW) project (2013–2016), which modelled interactions between these three aspects (Eker et al. 2018) and led to close collaboration with an extensive body of stakeholders from government, industry, NGOs and community groups (Macmillan et al. 2016).

This project fostered the development of a novel research framework, supporting the Institute in responding to policy-linked research opportunities in a timely manner and in dynamically maintaining research leadership in the field. For example, the principles of transdisciplinary working and systems thinking were central to the Complex Urban Systems for Sustainability and Health (CUSSH) project (2016–2024), and a participatory system dynamics modelling process was undertaken in Thamesmead (London), the project's flagship case study in the London strand of work. Different project partners worked in collaboration with government organisations, NGOs, resident representatives and a housing association to map stakeholders' perceptions of the blue/green/built infrastructure and to model and simulate systemic interventions for improving the use of natural space, leading to sustainable decisions (Pluchinotta, Salvia & Zimmermann 2022; Pluchinotta et al. 2024; Salvia et al. 2022; see also Figure 2 for an interactive simulation environment on people's use of natural space: https://exchange.iseesystems.com/public/ucl/thamesmead-use-of-natural-space--health/index.html#page1).

Similarly, inter- and transdisciplinarity were at the heart of other projects: the Community Water Management for a Liveable London (CAMELLIA) project (2018–2025) brought together system dynamics skills and stakeholders to promote sustainable water management and a better environment in London (Zimmermann & Pluchinotta 2020; see also Figure 3). In the VENTURA project (Virtual Decision Rooms for Water Neutral Urban Planning, 2021–2024), the integration of participatory system dynamics with GIS-based modelling facilitated a holistic understanding of specific policy issues and broader governance challenges (Mijic et al. 2023; Zhou et al. 2024a).

We have also applied a systems thinking approach in sociotechnical studies, by capturing and interpreting the complex interactions between the performance of complex technologies, such as heat pumps, and user behaviour. This has enabled the formulation of theory on user-related structures responsible for the underperformance of heat pumps in the UK, and highlighted the importance of user-oriented technological advancements and policies that support behaviour change (Oikonomou et al. 2022).

In the Policy and Implementation for Climate and Health Equity (PAICE) project (2023–2026), we strengthen the connection between greenhouse gas emissions and population health and health equity. Using systems and transdisciplinary approaches, we collaborate with stakeholders to identify shared priorities, gain insight into current and planned policies, build systems models to evaluate their cross-sectoral impacts, consolidate a monitoring framework, and assess and expedite implementation. Overall, these initiatives have reinforced our Institute's commitment to transdisciplinary systems research within the built environment.

1.2 Development of methodology

We also focus on the further development of transdisciplinary and systems methodology innovation. For example, we have advanced methods for developing models from textual data (Eker & Zimmermann 2016) and for understanding interdisciplinary communication in workshops, including a framework for analysing the micro-dynamics of communication (Zimmermann & Curran 2023). We have also developed a methodological framework to support the quantification of system dynamics models in the case of data scarcity (Pluchinotta, Zhou & Zimmermann 2024). We deepened the discussion on the importance of eliciting stakeholders' perceptions of system boundaries for problem structuring and decision-making, and proposed a methodology for eliciting and analysing differences (Pluchinotta, Salvia & Zimmermann 2022). In addition, colleagues within IEDE were involved in a study to develop a new model of transdisciplinary health research based on the reported reflections of recent studies. They built on the work of Stokols et al. (2013) to develop a new model for transdisciplinary research, tested with researchers, which includes six interconnected and iterative phases: co-learning; (pre-)development; reflection and refinement; conceptualisation; investigation; implementation (Pineo et al. 2021). Colleagues also evaluated approaches and progress on implementing transdisciplinarity (Moore et al. 2023). These collective efforts underscore our commitment to pioneering innovative methods that support transdisciplinarity and systems perspectives.

Figure 2. Interactive simulation environment on people's use of natural space in Thamesmead, London (Image credit: Irene Pluchinotta)

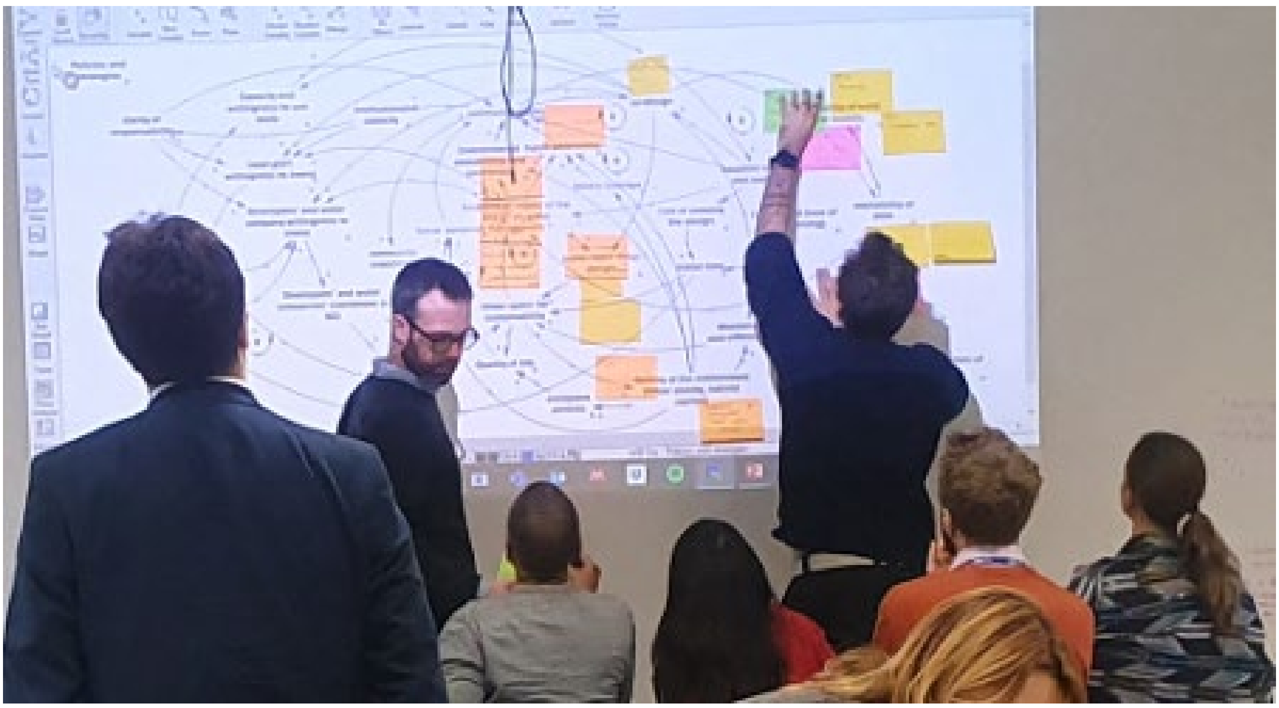

Figure 3. Developing a theory of change for the CAMELLIA project (Image credit: Irene Pluchinotta)

1.3 Focus on implementation

We are committed to making a positive difference. One example of our focus on implementation is the Evaluation Exchange (https://www.ucl.ac.uk/bartlett/environmental-design/research-projects/2024/oct/evaluation-exchange). The Evaluation Exchange is a transdisciplinary, extended learning programme that brings together UCL researchers and postgraduate students with voluntary and community sector organisations to tackle a research and evaluation challenge that each organisation faces (such as designing an evaluation plan, developing surveys or analysing existing data). The programme provides an opportunity to connect different forms of knowledge: – to link the know-how with the how-to – leading to the application of appropriate, relevant research outputs embedded within organisations.

We focus on implementation from a research design and evaluation perspective. Drawing on ideas from systems thinking programme evaluation and transdisciplinarity, team members developed theories of change that guided the design of large research programmes (Moore et al. 2021). As the research has evolved, they have also evaluated methods as well as progress on implementing transdisciplinarity (Moore et al. 2023).

The research team at IEDE has also used systems thinking to support policy. For example, we helped a government department understand how to motivate homeowners to improve the energy efficiency of their homes. To better support this research, we also developed methods to improve stakeholder representation in group workshops (Cunico et al. 2023). In the Co-creating Systems Thinking with Policy (CoSTiPoS) project (2022), we worked closely with the Government Office for Science and the Royal Academy of Engineering and analysed the factors that help and hinder policy makers from adopting systems thinking (Nguyen et al. 2023a, 2023b). Through the Construction Product Systems Mapping (COPSYM) project (2023–2024), we supported the Office for Product Safety and Standards in developing a systems perspective around the performance of construction products (Aguiar Rodriguez et al. 2024). As part of the ClimaCare project (2021–2024), we organised participatory workshops with a multidisciplinary stakeholder platform of experts to develop guidance for care home managers, local authorities, regulators and policymakers through a systems thinking approach. This guidance addresses the overlooked research area of overheating in care settings and develops strategies to protect the UK care system from future heat-related climatic effects (Oikonomou et al. 2023). These initiatives exemplify our approach to bridging academic research with practical applications, fostering collaborative solutions that not only address immediate challenges but also build systems that are sustainable based on a wide range of interdisciplinary evaluation criteria.

1.4 Engaged education

Finally, our work in transdisciplinary research and systems thinking not only advances the field but also enriches our education and citizenship work. We have integrated these approaches into our curriculum and pedagogical methods (Moore & Xypaki 2023; Zimmermann 2022), providing students with a comprehensive understanding of complex real-world challenges. We have also cultivated a collaborative culture within the department, notably through the Evaluation Exchange, which develops students' interdisciplinary teamwork skills.

2. Research Challenges

Transdisciplinarity and systems thinking are inherently interconnected, as both approaches involve looking at the world from multiple perspectives to achieve positive change. Our Institute's other Research Themes develop innovative solutions to problems, and our research contributes to the task of understanding why these solutions are not taken up and why these problems are still not addressed in an integrated way. Within this context, the implementation of innovative action is one of the research challenges we identify. In addition, our research suggests that embedding systems thinking in policy and decision-making supports the achievement of sustainable action, and is therefore an important prerequisite and a further research challenge we address. For example, our research on the UK policy context revealed that policy makers are increasingly interested in systems thinking, but they lack easy-to-use approaches that are fit for purpose for a fast-paced policy context or the ability to implement novel approaches (Nguyen et al. 2023a, 2023b). In our research on systems thinking approaches to support decision-making, we focus on the challenges and complexities of institutional dynamics, environmental decision-making and stakeholder engagement. We seek ways to further integrate operational research and management theories, such as attention-based views, in our research (Zhou et al. 2024b; Zimmermann 2011); we explore the boundaries and decision-making processes across organisational groups (Pluchinotta, Salvia & Zimmermann 2022); and we are interested in how to support the co-design of decision options in multi-stakeholder settings.

To enhance the implementation of innovative and sustainable actions, we also recognise the need for a greater understanding of change and transformation themselves (Pohl & Hirsch Hadorn 2007, 2008) – for example, through theoretical models that cater for stakeholders' perspectives, values and influence. Therefore, we are interested in applied models such as theories of change. However, the implementation of change can have unintended consequences and seriously damage the health of people and the planet. Thus, we also strive to understand the intended and unintended consequences of suggested actions.

For example, our recent research has highlighted substantial challenges in the social housing sector emerging from complexities in decision-making processes (Zhou et al. 2022). These are compounded by different understandings of system structure, divergent goals (e.g. health, sustainability) and growth-dependent mechanisms, leading to the reinforcement of (un) intended consequences that impact residents' health and wellbeing, and the provision of social homes (Pagani, Zimmermann & Davies 2023; Pagani et al. 2024a, 2024b). Our participatory activities showed the potential of using causal loop diagrams (CLDs) as boundary objects to support stakeholders in formulating transformative systemic interventions that challenge the current economic growth paradigm and their own world views (Pagani et al. 2024a).

In addition, to enhance systems and transdisciplinary research, we investigate how we can use visuals as boundary objects. We are interested in how these visuals can help create useful theories of change and how they can help the parties involved understand how their perspectives and work relate to each other. We aim to create a holistic and feedback-focused view that helps a team understand (un)intended effects of decisions and actions. To enhance the quality of participatory work with stakeholders and diverse teams, our research focuses on participatory engagement itself, examining how to foster understanding across disciplines and perspectives. We tackle this challenge by conducting micro-analyses of communication and actions in participatory settings. To understand workshop micro-dynamics, we have developed frameworks for such analyses and introduced a novel dynamic perspective regarding how interdisciplinarity evolves in a group setting (Zimmermann & Curran 2023).

All these challenges open avenues for future research agendas on innovative and creative ways to tackle them.

3. Setting the Research Agenda

In imagining and planning our research for the next decade, our group wants to continue combining systems thinking and transdisciplinary research and practice. We will continue to focus on learning from case studies, stories and practice in our cross-boundary work to better understand how we can change and transform our environments and to implement environmental, social and policy actions. We want to share tools so that our community can be reflective with their own work in a common research culture. To become more effective, we will embed different forms of evaluation and learning (i.e. adopting participatory, developmental, creative methods), exploring what works and what does not, and how we can consistently improve our practice.

One of our objectives is to drive change by promoting the uptake of systems thinking and transdisciplinarity, embedding it in different settings – for example, when supporting policy and decision-making processes.

As our work has shown that practitioners find the complex and divided language used across disciplines difficult to navigate, we will focus part of our efforts on capacity and capability strengthening. This would mean developing accessible language and easy-to-use tools that resonate with individuals' and organisations' existing experience.

Methodological innovation and adopting novel integrated approaches to address our research challenges will continue to guide us. Our approach will also expand on mixing methodologies, such as different modelling methodologies, including qualitative and quantitative ones. We are passionate about finding ways for stakeholders and project partners to bring their different perspectives and backgrounds to generate different kinds of knowledge. True to the co-creative identity of our group, we want to keep celebrating this diversity. We aim to integrate the diverse perspectives and find ways to leverage and value these differences. We want to do this by fostering a methodologically sound arena, where stakeholders and academics can come together to exchange and create knowledge. Our emphasis on methodological robustness and innovation will empower us to enhance our participatory methods, language and tools.

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Expert workshops: Reflections and future research pathways

Following an internal workshop with Theme members to develop an initial CLD identifying key research gaps, the Systems Thinking and Transdisciplinarity Research Theme hosted an international workshop to refine these ideas. Experts gathered to discuss research needs in the field and strengthen collaborations. The collaborative event began with an overview of systems thinking and the initial CLD, with participants validating and expanding on the diagram. The 15 participants from academia and practice (see Table 1) then mapped research challenges and future pathways.

The Systems Thinking and Transdisciplinarity CLD (Figure 4) highlights the interconnected factors influencing research and practice in these fields. Through discussion, participants refined the CLD, resulting in a clearer understanding of how systems thinking and transdisciplinarity can be applied effectively to complex research challenges.

Participants suggested several key themes that are integrated in the final model as reinforcing loops (R):

- **Use of transdisciplinary research:** Participants highlighted the importance of research teams' ability to bridge disciplines and knowledge, thereby advancing their use of transdisciplinary research. Such use can then foster learning about transdisciplinarity, further encouraging its broader application (Reinforcing Loop R1).
- **Balancing power dynamics:** Emphasising equitable representation in transdisciplinary research, participants identified balances of power and involvement of diverse perspectives and knowledge as crucial for diverse knowledge integration and collaboration (Reinforcing Loop R2). As a participant noted, "the two biggest ones [factors] being the exercise of political power and the delivery of finance and resources".
- **Micro-dynamics in workshops:** Participants discussed the importance of understanding workshop micro-dynamics for a tailored workshop design, fostering better group dynamics and more effective collaboration (Reinforcing Loop R3).

Table 1: Workshop participants

Name	Affiliation
Claudia Binder	EPFL
John Clarkson	University of Cambridge
Martijn Eskinasi	Dutch Ministry of the Interior and Kingdom Relations
Andreas Größler	University of Stuttgart
Indy Johar	Dark Matter Labs
David Lane	University of Reading
Roderick Lawrence	University of Geneva
Tobias Luthe	ETH Zurich
Josephine Musango	Stellenbosch University
Lawrie Robertson	Buro Happold
Etiënne Rouwette	Radboud University
Krystyna Stave	University of Nevada
Meike Tilebein	University of Stuttgart
Cobus van Rooyen	Arup
Elanor Warwick	Clarion Housing Group

- **Communicating complexity effectively:** Participants stressed the importance of effective communication of complexity to improve understanding of change and transformation, particularly across disciplines (Reinforcing Loop R5). One participant suggested that we "locate people so [they] begin to understand each other in the disciplines before they try and understand the system that they're working within".
- **Evaluating systems thinking:** Suggestions focused on the impact of evaluating systems thinking efforts for its future applications. Reinforcing Loops R7 and R8 show that the application of systems thinking to research improves the availability of fit-for-purpose approaches and tools and that positive experiences with systems thinking can bolster perceived value and trust in systems thinking and transdisciplinarity.

In addition to these reinforcing loops, participants also identified balancing feedback dynamics (B):

- **Tensions in perspectives:** Participants voiced that the involvement of diverse perspectives and knowledge enriches the understanding of change but can also create tensions in perspectives (Balancing Loop B1), limiting future involvement of perspectives and understanding of consequences and change.
- **Resource demands of systems thinking and transdisciplinarity:** Embedding systems thinking in policy and decision-making may enhance not only positive but also negative experiences with systems thinking, influencing the perceived value of and trust in systems thinking and transdisciplinarity (Balancing Loop B2). Participants noted that resource demands and allocation play a substantial role in determining whether the positive or negative aspects prevail.

After identifying gaps, participants discussed future research pathways, with key points summarised below:

- **Openness to knowledge and approaches:** Participants considered creation of opportunities to exchange knowledge and openness to diverse approaches such as the qualitative and participatory methods important for bridging cross-disciplinary knowledges and enhancing transdisciplinarity.
- **Learning:** They also noted the importance of scientific evidence like evidence-based workshops and the importance of learning from case studies for designing tailored workshops, fit-for-purpose approaches and tools and practical understanding of change and transformation processes.
- **Tensions:** Rather than avoiding interdisciplinary differences, navigating and valuing of tensions can lead to constructive dialogue and improved outcomes. This approach ensures that all viewpoints are considered and integrated into the decision-making process. It can also drive the implementation of actions, using conflicts as opportunities for more innovative design of actions.
- **Language:** Participants considered clear communication of these concepts through accessible language as essential for effective communication of complexity, enabling stakeholders with diverse backgrounds to engage with findings.
- **Impact evaluation:** Finally, evaluation of impact and dissemination of these applications builds stakeholders' perceived value of and trust in systems thinking and transdisciplinarity. Transparent and rigorous evaluation processes demonstrate the effectiveness and benefits, thereby encouraging broader adoption and support.

Overall, participants also highlighted the importance of bridging between academia and the implementation sector for advancing systems thinking and transdisciplinarity in research and practice.

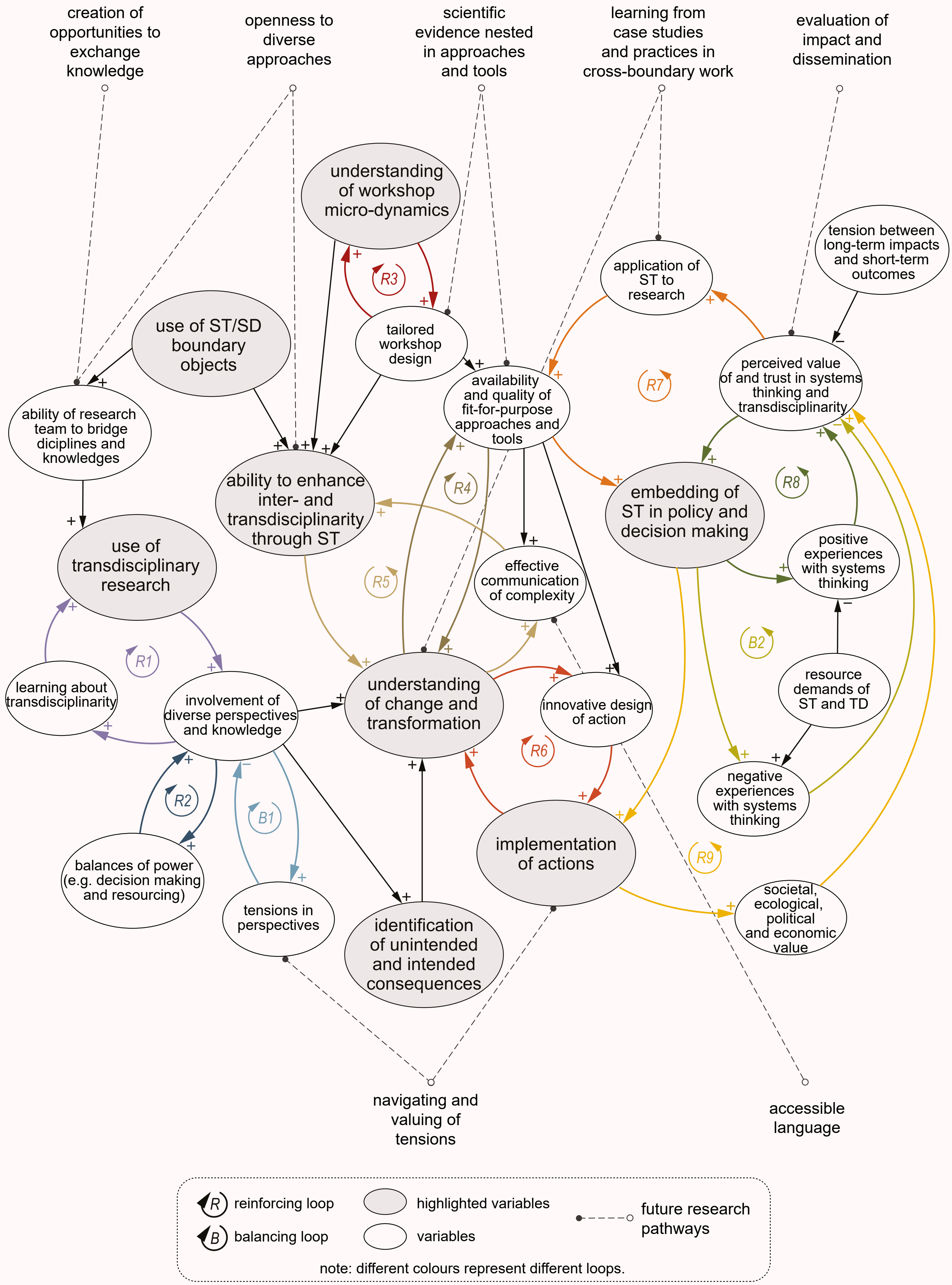

Figure 4. Causal loop diagram: Systems thinking and transdisciplinarity (Image credit: Yuhong Wang & Dajia Ke 2024)

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