REGENERATIVE DESIGN IN DIGITAL PRACTICE

A Handbook for the Built Environment

Edited by

Emanuele Naboni
Lisanne Havinga

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RESTORE
REthinking Sustainability
TOwards a Regenerative Economy

Cover Image - The Spiral, New York

Located at the intersection of the High Line and Hudson Park, The Spiral extends the green space of the former train tracks in a spiraling motion towards the sky – from High Line to the skyline. Reminiscent of the city's classic setback skyscrapers, The Spiral stands out for its shared open space on every floor. At each level along the ascending path a terrace connects to a double-height atrium for meetings and events with views across Manhattan.

Courtesy © Bjarke Ingels Group

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REGENERATIVE DESIGN IN DIGITAL PRACTICE

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Lisanne Havinga is a researcher at Eindhoven University of Technology (TU/e) in the Netherlands. Her recent work combines the use of Life Cycle Assessment, Hygrothermal Performance Assessment, Heritage Impact Assessment and Life Cycle Costing in the evaluation of the sustainable renovation of post-war heritage. She is currently project leader of the *'Renovation Accelarator'*, a project that is under development as part of the National Climate Agreement of the Netherlands, aiming to accelerate the large-scale renovation of the housing stock while achieving industrialization, innovation, and cost reduction. She is specialized in the interdisciplinary evaluation of design decisions, with a special focus on circularity and environmental impact considerations.

NOTES ON EDITORS

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Sergio Altomonte is Professor of Architectural Physics at the Université Catholique de Louvain (Belgium), where he is director of the research group Architecture et Climat. A fully-registered architect, he has held academic positions in the UK (Nottingham, 2007-17), Australia (Deakin, 2004-07) and Italy (Rome La Sapienza, 1998-2004). He has also held visiting positions at the Royal Danish Academy (Denmark, 2013-15) and the University of California, Berkeley (USA, 2012-current). His expertise lies at the intersection between indoor environmental quality, building systems and human comfort, health and well-being.

FOREWORD

I am honoured to write the foreword for Regenerative Design in Digital Practice. As I do this from a remote location on an island in the South Pacific in the middle of winter, unseasonably wild and heavy rain is battering the tin roof and a fire is raging in a battle to keep me warm. At the same time, Europe is in the grip of a record hot summer for the second time in as many years. There is no denying that the time for urgent change in terms of how we design and build our cities has now arrived. This is a unique period where multiple drivers of change, such as climate change, global biodiversity loss and urbanisation, are coming together and causing unexpected and rapid changes to human society.

Now, designers must grapple with more information than ever before, more digital tools and techniques to aid in design and a plethora of new technologies, but must operate with much less certainty about the future. We have a responsibility to ensure that what we design not only results in less ecological and cultural harm, but that our built environment begins to actually regenerate health; in all senses of the word. We are already very good at designing our buildings to shelter us from the heat of a hot sun, from rain and from wind (which I am very grateful for as I write this), but our buildings and our cities could and should be doing so much more. We already have the means and technologies to ensure that they could be generating energy and growing food, that they could provide habitat to non-humans, that they could filter and remediate air, water, and soil, that they could cycle nutrients, and could contribute to meaningful cultural and societal experiences. What we lack is a coordinated sense that this breadth of regenerative performance is what we should aim for in terms of built environment goals.

Regenerative Design in Digital Practice is therefore an exciting and significant addition to literature on this subject because it challenges thinking on built environment design. It is an important addition to resources that enable designers to begin to change not only their design processes and outcomes but also their consideration of appropriate and ambitious goals for the design of our cities, buildings and spaces. It brings together some of Europe’s most esteemed practitioners and researchers at the cutting edge of their fields to interrogate current practice and provoke debate and new perspectives in terms of regenerative design.

As I write this I am literally almost as far from Europe as one can be, but with a simple laptop and internet connection I can contribute to this important project and marvel at how digitally interconnected the world has become. We need to apply this same expectation of interconnectedness - this web of highly responsive relationships and feedback loops - to how we build our cities and how we expect our buildings to function over time. While the realm of the digital and the online can often be anywhere or everywhere, the realm of the physically built must become more site specific, more knowledgeable of local ecologies, climates, and peoples, and leverage this knowledge effectively for a new kind of design. Harnessing big data, and digital data collection and tools can help in this regard, and Regenerative Design in Digital Practice demonstrates how to do this.

It is my expectation that Regenerative Design in Digital Practice will enable practitioners and students to become fluent in the practice of regenerative design. My sincere hope is that these concepts and techniques described in Regenerative Design in Digital Practice will be put into action as soon as possible in buildings and cities across Europe and indeed globally.

Dr Maibritt Pedersen Zari

Victoria University of Wellington, Aotearoa New Zealand
Author of Regenerative Urban Design and Ecosystem Biomimicry

INTRODUCTION

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Lisanne Havinga *Eindhoven University of Technology (TU/e), the Netherlands*

Rapid industrialisation and population growth have contributed to the development of buildings and cities that interact little with their environment or users. Development has generally focused on fulfilling certain needs, such as aesthetics, function, fixed levels of comfort, and cost efficiencies. Minimal consideration has been given as to whether buildings go well with, and harmonize with, the natural environment and human life. The extensive damage that human activity has done to our planet and the ecosystems it hosts is increasingly acknowledged by science. There is a growing recognition that there is no planet B and that addressing the issues of climate change, biodiversity loss, mass extinction and environmental damage and pollution may be the principal challenges of our time. However, current policies and practices are not yet on course to meet these challenges. Sustainable development must replace the growth at any price philosophy and must drive the choices and actions of citizens, communities, businesses, scientists and governments.

In regards to newly constructed buildings, so-called 'green buildings' are now relatively common and regulations and certifications have become more and more ambitious. Although these buildings are coined 'green' because they have a higher environmental performance compared to typical buildings, they are generally aimed at reducing 'negative' impacts. Cole [1] identified eight attributes of sustainable building that are typically addressed in sustainability standards or certifications:

- Reduces damage to natural or sensitive sites
- Reduces the need for new infrastructure
- Reduces the impacts on natural features and site ecology during construction
- Reduces the potential environmental damage from emissions and outflows
- Reduces the contributions to global environmental damage
- Reduces resource use – energy, water, materials
- Minimises the discomfort of building occupants
- Minimises harmful substances and irritants within building interiors

However, the targets established by the Paris Climate Agreement [2], the United Nations Sustainable Development Goals (UN SDGs) [3], and the recent IPCC report [4] will never be achieved by simply slowing the rate of depletion and degradation of the environment and of human health. It is becoming increasingly clear that a net-positive approach is needed to meet these targets and to undo the damage that has already been done. Moreover, while the complex challenges surrounding sustainable development have traditionally been viewed through a reductionist mono-disciplinary lens, the UN SDGs are promoting far reaching sustainability with proactive, global social goals, which can only be addressed by means of a holistic approach. Rephrasing the above-mentioned attributes of sustainable building to a net-positive and holistic approach would then imply a truly sustainable building:

- Increases the value of natural and sensitive sites
- Creates new ecological infrastructure
- Enhances natural features and site ecology during construction
- Repairs environmental damage from emissions and outflows
- Contributes to global environmental regeneration
- Creates new energy, clean water, and materials by circular approaches
- Increases the comfort and well-being of building occupants
- Creates beneficial substances within the building

This net-positive and holistic approach is a radical change of perspective that can be described with the expression ‘from less bad to more good’. This is the core principle of regenerative design. Regenerative design is built on the awareness that humans and the built environment exist together with natural systems. As such, Regenerative Design is aimed at reversing damage that has been done, restoring ecosystems and allowing them to thrive and evolve.

Designers thus need to create and retrofit cities and buildings to be the catalysts of positive change. Design can no longer be merely concerned with developing artefacts that produce limited environmental impacts within a specified target, or that limit impacts on people’s health within a certain threshold of emission. Instead, buildings must be developed with the aim of enhancing the relationships between global natural systems, the built environment, and the inhabitants over a long period.

This book explores how the concept of regeneration can be – and is starting to be - explicitly applied to the design of cities and building. A 'proactive' design approach is proposed which seeks to integrate regenerative design principles into the concepts and workflows of practitioners, researchers and students. A regenerative design process considers the key positive interactions between the built, human and natural systems. By promoting these positive interactions, which range from supporting local ecosystems to employing construction techniques that promote a circular use of building components, the designer blends creativity and science.

Regenerative design necessitates an understanding of the local dynamics of a project and the interactions with the local climate and living natural systems. Which in turn necessitates an understanding of the layered network of (among others) climate, geology, ecology (mineral and other deposits, soil, vegetation, water and wildlife, etc.), and human health, and its complex interactions. Therefore, designers need to be able to operate beyond conventional construction practice; they have to be trained to adopt interdisciplinary and multifaceted systems thinking. To achieve regenerative design, in addition to measuring numerous environmental, social and economic impacts, design practitioners of the built environment need to focus on understanding and mapping their relationships.

This book aims to fill a gap in existing literature by introducing the fundamental design principles of regenerative design practice by acknowledging the potential and the need to integrate science, big data and digital tools in the design process. The book serves as a guide to the implementation of regenerative design and the digital tools that can be adopted to achieve it.

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SUMMARY

Emanuele Naboni *KADK Copenhagen, Denmark*
Lisanne Havinga *Eindhoven University of Technology (TU/e), the Netherlands*

REGENERATIVE DEFINITIONS FOR DESIGNERS
THE PILLARS OF REGENERATIVE DESIGN

The first chapter develops within the background given by the Paris Agreement, UN Sustainable Development Goals and the Living Building Challenge. The chapter outlines the definition and principles of regenerative design. Three pillars of regenerative design are identified. It is argued that the inclusion of science and digital tools in design should converge toward design solutions where regenerative targets, outdoor comfort, indoor wellbeing and circular economy principles are negotiated. In addition, it outlines the current state of regenerative design in practice and outlines barriers to its broad implementation. Furthermore, it elaborates on the integrated nature of regenerative design challenges, and the need to blend a wide range of sciences in order to meet these challenges.

TOOLS AND DATA FOR HOLISTIC MODELLING
SIMULATING REGENERATIVE FUTURES

The second chapter focuses on novel digital tools and software applications that support regenerative design. The focus is on models that support an interdisciplinary evaluation of performance. The chapter showcases how computational optimization techniques can assist in achieving regenerative design targets. Furthermore, the integration of big data is discussed. The added value of tracking global and local flows of data concerning the climate, ecosystem, flows of materials, emissions, human health and individual physiological parameters is explained. It is shown that the integration of digital tools and big data is imperative in achieving regenerative buildings.

CLIMATE AND ENERGY
LOCAL CONTEXT, ADAPTATION AND RESILIENCE

The third chapter focuses on the ways in which the built environment interacts with the local climate, and how it can be designed in ways to optimize regenerative performance targets such as indoor and outdoor comfort, resilience to climatic events, and heating and cooling loads. One of the discussed factors that affects resilience is the urban microclimate due to its impact on walkability, comfort and health in urban spaces. Furthermore, the role of microclimatic design in improving not only the outdoor environmental thermal comfort but of restoring the local ecosystem (supporting wildlife habitat connectivity) is described. Finally, it is discussed how a positive energy exchange with the surrounding built environment requires the effective management and storage of excess renewable energy produced. In addition to a two-way trade with the district energy systems, this would allow an existing building to implement energy sharing strategies and initiatives with surrounding buildings and infrastructure.

CARBON AND ECOLOGY WITHIN THE DESIGN PROCESS
ENVIRONMENTAL IMPACT ASSESSMENT

The fourth chapter deals with the reduction of the environmental impact of both new and existing buildings, which is key to meeting the climate goals and mitigating the extent of global warming. The chapter fully embraces the concept of the circular economy in which growth and prosperity are decoupled from natural resource consumption and ecosystem degradation. Moreover, digital tools and approaches are explored that can be used to reduce the environmental impact of buildings and move towards buildings that have a positive impact on the environment. As such, the integration of life cycle assessment (LCA) in the design process is described, which – although gaining momentum and starting to be implemented in certification schemes – is far from standard practice. This integration is described from multiple perspectives, ranging from large scale urban LCA's, to parametric building LCA's and explorations of the sensitivity of LCA considerations.

HUMAN WELL-BEING VIA CERTIFICATION AND TOOLS
COMFORT, HEALTH, SATISFACTION, WELL-BEING

The fifth chapter focuses on the implementation of wellbeing and health in design. The purpose of this chapter is to outline the meaning(s) of health and well-being and to regulate the likely effects and prospects for design. The weight here is on the making of well-being as per the regenerative paradigm, versus the reductionist approach of sustainable design that targets the absence of ill health. This is well pictured by the term coined by Aaron Antonovsky, Salutogenesis, which means ‘generation of health’. One of the key references in this chapter is the Well Building Standard, which aims at implementing, validating, and measuring features that promote human health and wellness. While other chapters tend to have a focus on simulation models and assessment tools, this chapter has a focus on measurements, for example through exemplification of accessible and self-built tools and devices that collect information.

CASE STUDIES OF REGENERATIVE DESIGN
FROM PRINCIPLES TO REALISATION

The first five chapters discuss the principles of regenerative design and its application through digital tools in the topics ‘Climate and Energy’, ‘Carbon and Ecology’, and ‘Human Well-being’, and present novel tools, workflows, and examples of their application. Chapter six, however, aims to showcase examples that are currently at the forefront of regenerative design in practice. Firstly, three well-known international examples are discussed, and subsequently, a range of case studies is discussed more in-depth. The aim is to both connect case studies to theory as well as derive theory from case studies. Most presented case studies cover multiple pillars that have been introduced in the preceding chapters.

ACKNOWLEDGEMENTS

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The conception of this book originated in 2017 when the activities of working group 2 of the RESTORE Cost Action began. We understood that regenerative design was mainly a theoretical concept, and that it was disconnected from the digital innovation that is taking place in science and in practice. We identified the scientific areas of concern and started an intense dialogue with the associated key players. In late 2018, we organized a conference and training school in Malaga where we were able to meet and elevate the discussions to a higher level. A community was created based on the activities in Malaga, and this community was extended to include other key international players, each bringing a unique perspective to and expertise in regenerative design. Thanks to the valuable contribution of the RESTORE Cost Action, the commitment of the participants of the Malaga conference and training school, and the extended network of outstanding practitioners and researchers, we are now able to write the acknowledgements of the book 'Regenerative Design in Digital Practice'.

Firstly, we would like to thank the 61 contributors to the book who volunteered their time to help explain and evidence their experiences in developing regenerative cities and building projects, which form the basis for this book. It is our belief that the diversity of the contributors is in large part the reason for the success of this book. The contributors:

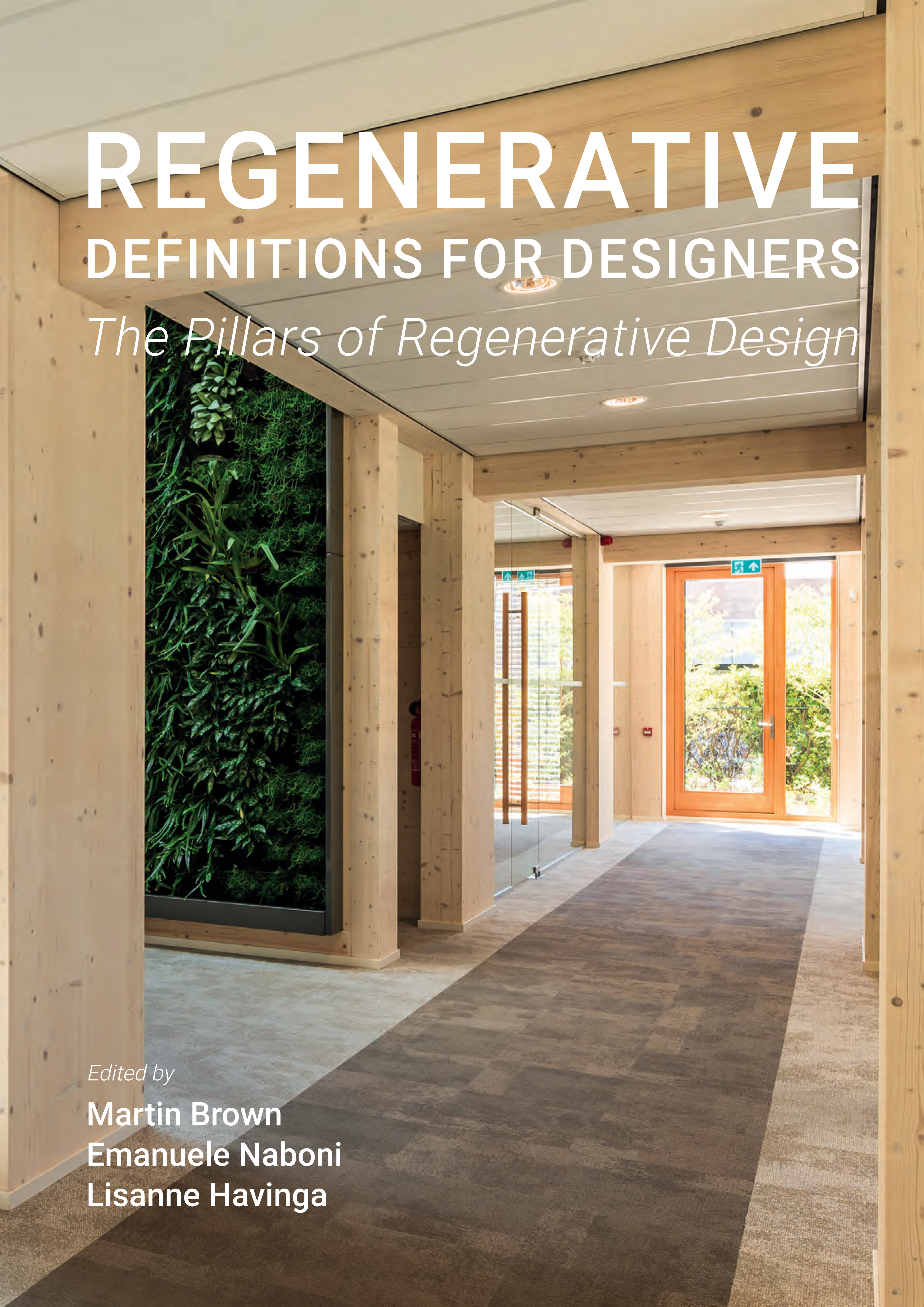
- range from the United States to Denmark and from Singapore to Italy
- range from well-known international architectural offices to young engineering consultancy firms
- range from established professors to PhD researchers
- range from the discipline of human metabolism to architectural design and from ecology to urban physics.

This diversity, which is crucial for this book, is reflective of the interrelated and complex challenges posed by regenerative design ambitions.

But this effort of organising such a diversity of topics would never have been possible without those who contributed to the book in the role of chapter editors. With them, we had several thematic discussions that helped to develop the vision and foci of the book. We would thus like to express our sincere gratitude to the chapter co-editors for their help in coordinating, reviewing and editing the chapters. The effort and expertise of Martin Brown, Clarice Bleil De Souza, Terri Peters, Ata Chokhachian, Luca Finocchiaro, Catherine De Wolf, Antonino Marvuglia, Angela Loder and Sergio Altomonte – and the numerous rounds of reviews they were involved in – made it possible to for the book to provide a clear and coherent picture of current regenerative design practice and future directions.

Secondly, we would like to thank those involved in the management, administration and editing of the book. We would like to thank the fellow RESTORE management committee members, including Carlo Battisti, Martin Brown, Roberto Lollini and Andras Reith, who helped guide the core principles of the book. In addition, Eurac – being both the publisher as well as the grant holder of RESTORE – provided professional and courteous support at all times. The relationship between author and commissioning editor is an interactive one. On this occasion matters ran smoothly not least because of the help of Gloria Peasso. In addition, a sincere thank you to Duncan Harkness for his diligent proofreading of the book and his sharp eye for argumentative clarity.

Last, but certainly not least, we would like to thank the institutions that created the opportunity for us to edit this book. Emanuele Naboni wishes to thank the Royal Danish Academy of Architecture, Design and Conservation (KADK) for its support of this project, particularly Jakob Knudsen, Natalie Mossin and David Garcia for setting a regenerative agenda in our practice of research and teaching at KADK. Lisanne Havinga would like to thank Eindhoven University of Technology for their support of this project and for providing a research environment in which an interdisciplinary and evidence-based approach is celebrated and fostered.



REGENERATIVE
DEFINITIONS FOR DESIGNERS

The Pillars of Regenerative Design

Edited by

Martin Brown
Emanuele Naboni
Lisanne Havinga

Chapter Cover Image - Geelen Counterflow, NL

Considered to be the most sustainable office building in the world, the office of Geelen Counterflow in the Netherlands generates 50% more energy than it uses for heating, cooling and other energy demands. The structure is made up of sustainably sourced timber, without the use of glue, screws or nails. A natural garden was designed in a way to support and enhance local ecosystems.

Courtesy Geelen Counterflow © John Sondeyker

REGENERATIVE
DEFINITIONS FOR DESIGNERS

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DEFINING REGENERATIVE DESIGN

Martin Brown *Fairsnape, United Kingdom*
Emanuele Naboni *KADK Copenhagen, Denmark*
Lisanne Havinga *Eindhoven University of Technology (TU/e), the Netherlands*

We are now aware - and may be the first generation to be aware - of the global impact that the built environment has on climate change. The construction and operation of buildings account for nearly 40% of energy-related carbon dioxide (CO_2) emissions [1], and as such, contributes greatly to the climate change problem. Regenerative design is concerned with aiming to achieve the opposite: for buildings to become part of climate change solutions. There is an urgent need to make this transition. Reports from the IPCC warn us that we have 12 years, until 2030, to take significant and radical steps to reduce carbon emissions [2]. This means that projects currently within the briefing, design or in construction stages are those that will start to function within the 12-year window - and consequently, are the designs that need a radical, regenerative makeover, today. This requires buildings to be constructed and to operate not only without fossil fuels but to be net carbon positive, and for buildings to sequester more carbon and to produce more renewable energy than is used during their construction, operation and disposal. A phenomenal ask.

The built environment no longer has the luxury of just being ‘less bad’, but, with urgency, needs to adopt net-positive, regenerative sustainability thinking to incrementally do ‘more good’ [3]. This thinking involves envisioning homes, workplaces, neighbourhoods and cities that are socially just, culturally rich and ecologically regenerative [4]. Designers have often created cities and buildings that are dependent on a one-way flow of energy, materials, and living substance from nature toward human society. Conversely, as widely discussed in this chapter, regenerative design is aimed at enhancing human life and natural ecosystems in a partnered relationship. The focus of the chapter is to set key regenerative design principles and to explore the integration of these principles in practice. As such, the topic is framed from the perspective of implementation by architects, engineers and urban planners. Three key pillars of implementation are outlined, which relate to climate, circular economy and health.

FROM SUSTAINABLE TO REGENERATIVE DESIGN

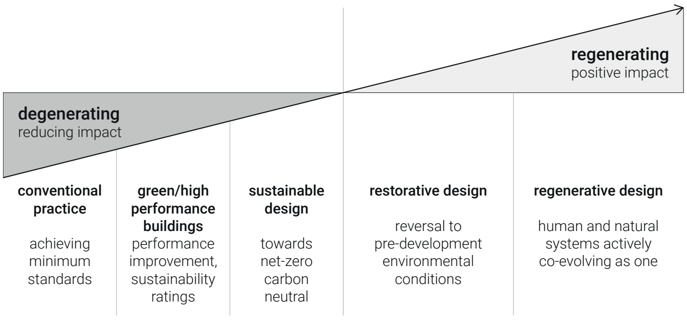
Regenerative Design is an approach that aims to create a new set of relationships that reinforce the state of health of human and natural ecosystems, utilising appropriate construction and technology. This challenge implies an in-depth knowledge of multiple fields, and thus the involvement of several specialists and adequate tools to develop and frame approaches and solutions. Such tools and proper guidance are needed to support designers in addressing this complex challenge.

Today's responses to climate change and biodiversity issues are inadequate given the urgency and scale of the predicted impacts. Current targets tend to aim to reduce the negative impact, or at most aim for 'neutral' operational energy use. It is, however, becoming clear that newly constructed, and renovated buildings need to go beyond reducing environmental impact; they must have positive environmental benefits. A holistic approach is needed that included carbon, resource use, waste and water. Regenerative design practice aims to not only mitigate but also to reverse the causes of climate change and ecosystem degradation (Figure 1).

In the 1970s, US landscape architect John T. Lyle pioneered the term 'regenerative design' in his book entitled *'Regenerative Design for Sustainable Development'* [5] (the term had already been formulated earlier by Robert Rodale in relation to agriculture [6]). Recently, regenerative design has come to the forefront of sustainability thinking, with scholars such as Bill Reed and Raymond J. Cole exploring its definitions and application [7]–[15]. The publication '*Sustainability: Restorative to Regenerative*' [4], presented an overview of this thinking and established a set of definitions:

- *Sustainability*. Limiting impact. The balance point where we give back as much as we take.
- *Restorative*. Returning social and ecological systems to a healthy state.
- *Regenerative:* Enabling social and ecological systems to maintain a healthy state and to evolve.

Figure 1
While current sustainability practices focus on moving from the conventional practice of degeneration to a neutral impact, restorative design aims to restore ecosystems, and regenerative design aims at allowing human and natural ecosystems to evolve. (Adapted from [15], [16])



EGO ECO SEVA

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Global Assessment Report on Biodiversity and Ecosystem Services [17], launched in May 2019, revealed that one million species are at risk of extinction over the next decade. With land and built environment development being one of the main causes, we urgently need to embrace a new relationship with nature and the natural environment.

This shows that humans have been making decisions apart from nature. Conversely, we need a clear understanding of and a willingness to embrace the emerging worldview paradigm, where we as humans make decisions (and undertake design) as 'part of nature' not 'apart from nature'. *'We are developing a worldview which is the understanding of our position on the planet, and has a crucial role in building the awareness for regenerative sustainability, and understanding the true influence of the built environment'* [4].

Regenerative sustainability is framed within the Ego-Eco-Seva concept [4]:

Ego. From the industrial revolution, as humans, we assumed 'man's tyrannical dominion' over the earth's resources and life forms, founded on a linear take-make-dump mentality. We have moved on from a 'dump' approach to our unwanted products, waste and buildings to a more considered 'dispose of', yet a linear mentality that exists within our built environment.

Eco. The current and dominant sustainable design and construction discourse triggered and reinforced by the Brundtland definition (of doing nothing today to compromise tomorrow's generation). This is a promise that we are failing to keep. We have compromised today's generation and, unless meaningful change to current practices is realised, will continue to compromise future generations through, for example, human-made climate change, increasing carbon emissions, poor air quality and the worsening health of those who work, live, learn and play in our buildings.

Seva. Represents a regenerative worldview in which we embrace living systems of the planet with love and care. Seva (service) translates into actions we take when tuned into nature, where we see ourselves as a part of, not apart from nature and in which we add more than we subtract from living systems. In practice, this means a dedication to healing the future, through repairing the damage that has been caused by our previous designs, which exceed the planetary resilience boundaries.

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TOWARDS A SOCIALLY JUST, REGENERATIVE ECONOMY

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Current and emerging regenerative economic thinking is challenging the established views of economics at the macro, micro and meso levels of the built environment. The reasoning from work in the UN Sustainable Development Goals, the Circular Economy and Doughnut Economics is breaking down the economic orders of linear economies and ever-growing gross domestic products. We see a new standard language for economics emerging, one that has left behind a commercial language of war, conflict and oppression for an emerging language of sharing, circularity, and love (seva) [1].

SUSTAINABLE DEVELOPMENT GOALS

The Sustainable Development Goals [2] are giving new purpose to businesses, their buildings, and how they are designed, constructed and used. Indeed, concerning building sustainability, we need to elevate our conversation to include social justice and regenerative economy issues alongside climate change and resource considerations. The influence of our built environment ripples into almost every industrial, commercial and domestic sector, in turn, influencing those sectors' capability for sustainability. We need to understand this influence and act with due responsibility through sound governance. The Sustainable Development Goals provide a framework for this understanding.

Beyond the 17 colourful SDG icons, 169 targets with 232 indicators are set, which are designed as a plan of action for people, planet and prosperity that seeks to strengthen universal peace by 2030. Adopted by all UN Member States in 2015, the SDGs set out a framework and a challenge for humanity to decouple economic growth from climate change, poverty and inequality. It is very much a proactive approach that is rapidly replacing the now considered passive Brundtland definition of *'meeting the needs of the present without compromising the needs of future generations'*. Many built environment client, design and construction organisations are reframing their sustainability initiatives and/or targets to align with the 17 goals.

It is by coincidence, serendipity or just good fortune that the 2030 SDG target date falls within the recent IPCC report that details the immediate period in which we must take increasingly radical actions to avoid irreversible climate breakdown. This also resonates with the recent impassioned speech by 16-year-old Greta Thurnberg to the World Economic Forum [3], in which she challenged us with the metaphor '*our house is on fire*' and that we (i.e. the world's youth) '*don't want you to be hopeful, but to panic and put out the climate breakdown fire*".

CIRCULAR ECONOMY

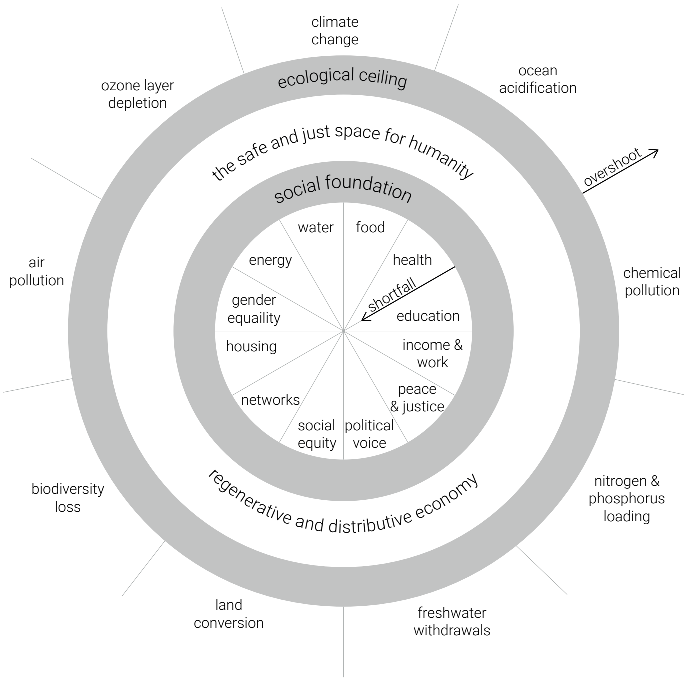
The Circular Economy was developed in parallel to regenerative design thinking. In his book titled 'Regenerative Design for Sustainable Development' [4], Lyle states *'A regenerative system provides for continuous replacement, through its own functional processes, of the energy and materials used in its operation'*. Lyle's work was part of the basis from which concepts such as Cradle-to-Cradle and the field of Industrial Ecology originated. Today, the notion of the circular economy, reinforced through the work and advocacy of the Ellen MacArthur Foundation [5], provides a set of principles that establish the criteria for regeneratively designed sustainable buildings: eliminate waste, pollution, negative social & environmental impact; keep products and materials in use; regenerate natural systems.

DOUGHNUT ECONOMICS

Kate Raworth's 'Doughnut Economics' [6] provides a new framework for economics, which, separate from the classic gross domestic product economic growth paradigm, measures economic performance based on whether the needs of people are met without damaging the earth. The 'doughnut' shape (Figure 2) illustrates this balance: the centre of the doughnut represents people that lack access to healthcare, education, nutrition, etc.; the outside of the doughnut represents environmental impacts beyond the planetary boundaries. As such, the model represents a safe space for growth within planetary boundaries and above a social foundation.

Figure 2

Doughnut Economics: an economic model measuring performance based on meeting people's basic needs while staying within planetary boundaries (Adapted from source: [6])



REGENERATIVE DESIGN

It is within this 'safe space', following the RESTORE sustainability definitions, the Four Laws of Ecology, the Sustainable Development Goals (SDG's) and the Circular Economy that regenerative design must operate if it is to design a thriving built environment that not only meets but betters the Paris Agreement and subsequent IPPC findings [7]) to achieve a future that is ecologically sound, culturally rich and socially just [8].

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THE PILLARS OF REGENERATIVE DESIGN

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Throughout this book, you will find considered narratives, detailed exploration and practical applications of digital tools, resources and frameworks that guide building and facilities designs towards a regenerative model based on these Pillars:

- Climate and Energy (chapter 3)
- Ecology and Carbon (chapter 4)
- Human Wellbeing (chapter 5)

CLIMATE AND ENERGY

Regenerative Design adapts to, harmonises with and enhances microclimates in a harmonious relation to larger climatic flows (e.g. thermal and water flows), through designs that are a part of nature, rather than 'apart' from nature. The balance of energy generation and use is positive.

Because there is a synergistic relationship between the climate, ecosystems and human life, strategies to address the causes and impacts of climate change may be found in managing local microclimates as a way to reduce and produce energy, eliminate and absorb emissions, tackle the loss of biodiversity and promote the life of people in outdoor spaces. This would mean at the same time restoring or creating ecosystem services, thus adding to the overall resilience of the built environment, creating favourable climatic conditions for people to spend more time in public spaces. Substantially people need to design with climate, design with nature and design with people in mind. New cities and buildings should provide substantial opportunities for initiating and demonstrating this change.

Professionals need to '*Design with Climate*'. This is also the tile of a book published in 1963 [1], which stood as one of the most pioneering books in the field of adaptation to climate. It remains a reference nowadays that climate change is an emergency. It includes principles from ecology, biology, engineering, climatology and physics, and proves how a systematic approach to climate change can be aesthetically sound.

This presents planners and designers with the significant challenges of rediscovering bioclimatic principles and learning to apply them to create innovative urban environments. These environments should be thermally liveable, and with positive energy and emission balances. Cities should be able to produce more energy than they use and absorb more emissions than they emit. Cessation and absorption of the use of GHG emitting energy sources contribute to reducing the causes of climate change.

Furthermore, professionals need to '*Design with Nature*'. This is also the title of the book written by McHarg in 1971 [2]. Design with nature means cities 'live with' rather than against the more powerful forces and flows of nature. Cities can cope with the reversing of climate change while concurrently responding to the degradation of ecosystems and the loss of biodiversity. With a shift of this kind, complex and mutually beneficial interactions between the built environment, the living world and human inhabitants may more readily occur. Ecosystems and the biodiversity within them can affect climate through interacting with surfaces, carbon storage in vegetation and soils, vegetation albedo, evapotranspiration, structural change in biological communities and peat-land methane emissions [3]. This is also the topic of the book '*Regenerative Urban Design and Ecosystem Biomimicry'*, written by Maibritt Pedersen Zari.

Finally, professionals need to '*design with people'*. If the integration of climate and nature is achieved, cities and buildings will play a crucial role in maintaining and improving people lives. It is thus necessary to promote outdoor thermal comfort, air quality and flood and water management to ensure the quality of outdoor experiences. Thermally tuned outdoor spaces that are pollution free, that connect people to nature, and that are safe in case of extreme climatic events could accommodate various outdoor activities and contribute greatly to urban livability and vitality. The co-evolutionary approach that is proposed here addresses climate change, ecosystem quality, energy and life in the city. These topics are all discussed in the chapter titled *'Climate and Energy'*.

ECOLOGY AND CARBON

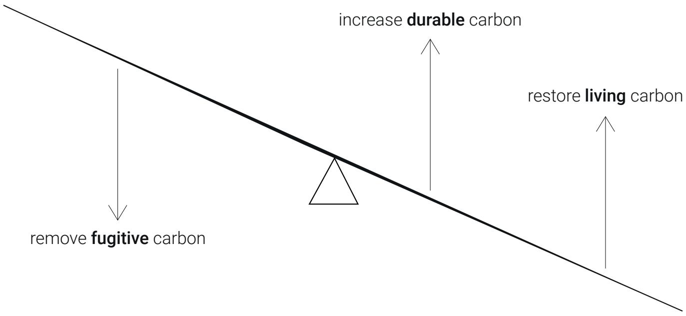
Regenerative Design reverses environmental impacts, with designs that are carbon positive, use clean energy, incorporate waste products and cleanse the air, water and soils, with a focus on reversing climate breakdown.

Regenerative Design keeps buildings and products in use as long as possible, creating designs with long, even undefined lives that have second and *future reuse potentials designed in.* While part of the damage done to the ecosystem may be irreversible, it is still possible with the use of a wide range of design measures to understand, control and enrich global eco-balances with a careful circular design. Barry Commoner's Four Laws of Ecology outlined in the first chapter of The Closing Circle [4], now seen as one of the foundations of the circular economy principles, provides a sound framework for ecologically based regenerative design:

- *Everything is connected to everything else.* There is one ecosphere for all living organisms, and what affects one affects all. The cities, buildings, components and products we design and inhabit are interconnected parts of an ecosphere.
- *Everything must go somewhere.* Instead of the current take-make-dispose system, natural ecosystems are circular: There is no waste. Regenerative design brings products and components from previous lives into buildings, and ensures future lives through circular economy principles.
- *Nature knows best.* Distrubances of natural ecosystems should be avoided by means of acting in line with natural processes and substances. Regenerative design should learn from nature and embrace natural materials and solutions.
- *There is no such thing as free lunch.* We need to design and to live within the balance of nature and planetary boundaries. Natural resources used should be seen as being on loan, to be paid back, and the longer we take to pay back the worse and more rapid our climate breakdown becomes.

Figure 3

Reimagine Carbon: reduce fugitive carbon, increase durable and living carbon storage in buildings and natural resources.



The 2016 update of the EPBD [5] mandates all member states to establish long-term building renovation strategies aiming at decarbonising national building stocks by 2050. In addition, during the May 2019 'Future of Europe' Sibiu Summit of EU leaders, eight countries called for the adoption of regulations requiring net-zero carbon emissions by 2050. However, reaching net-zero carbon emissions may not be sufficient: all detailed pathways for future CO_2 reduction proposed by the IPCC report incorporate carbon dioxide removal and net negative emissions to ultimately limit global warming to 1.5°C (after a potential overshoot).

We have an urgent need to reimagine carbon, not only to reduce fugitive carbon but also to increase durable carbon, carbon that we can lock into buildings and products, that within a circular, or better still a regenerative economy, can last for hundreds of years (see Figure 3). Also, regenerative design addresses and enables the vital increase in living carbons through embracing carbon benefits of living ecosystems. The IPCC's 12-year window to act highlights the importance of limiting the carbon we emit today. Instead of only evaluating the performance of the life cycle operational carbon, the carbon we emit today for tomorrow's buildings (i.e. the embodied and construction carbon) needs to be a strong focus. This is the focus of the chapter titled *'Carbon and Ecology'*.

HUMAN WELL-BEING

Regenerative Design focuses on salutogenic health and designs that are socially and culturally 'just'. Designs for indoor and outdoor environments must demonstrably improve inhabitant health, and not merely seek to reduce ill health.

We are increasingly aware that only reducing our impact is inadequate if we are to address the myriad health issues we face. We are also increasingly aware that our actions across the built environment, through commissioning, designing, procuring, constructing, operating or disposal, have a very significant impact on human health, for better or for worse. Architects can thus be seen as 'upstream doctors', as buildings contribute significantly to the population's health outcomes [6].

The interconnection between human health and the planet's health can be used as a driving incentive for regenerative design. This implies an in-depth knowledge and understanding of how the health of the planetary ecosystem connects with the health and well-being of people. Designers and built environment practitioners have only recently begun to understand the full impacts of building on health within the World Health Organisation definition.

Meaning 'the generation of health', salutogenesis describes an approach that focuses on factors supporting human health and well-being, not just on factors that cause ill health. An understanding of salutogenesis is key to progressing towards a regenerative built environment. Terri Peters, in *'Design for Health'* [7], asks the question: *'Can Architecture Heal?'* We are seeing evidence emerging [8] that it can and indeed is the role of Regenerative Design to ensure that it does. This is the focus of the chapter titled *'Human Well-being'*

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THE TOOLS OF REGENERATIVE DESIGN

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Today *'we have emerging strategies, approaches and tools that will allow systems to flourish and evolve'* [1]. These strategies, approaches and tools will aid and support regenerative design and include:

The education. Regenerative models, from natural ecosystems to regenerative cultures and communities, are increasingly part of the built environment curriculum, training workshops and conferences.

The thinking. Many of the greatest minds in ecology, sociology, biology, health and the built environment are setting out how we can make the regenerative journey

The language. From one of a combative, egotistic approach to design and construction, to one that embraces a worldview, seeing ourselves and our buildings as part of nature, rather than apart from it. [1]

The economic frameworks. The circular economy and doughnut economy are just two examples that are turning the take, make, dispose culture on its head. A transition to a Regenerative Economy entails changing the worldview; Fullerton and Hunter suggest *'a shift to an ecological world view in which nature itself is the model' and* that '*The regenerative process that defines thriving, living systems must define the economic system itself'*[2]. A regenerative economy redefines wealth in terms of multiple kinds of capital rather than just financial, including living, cultural, experiential, intellectual, spiritual, social, and material capital [3].

The standards. There are emerging sustainability standards that promote regenerative practices. Examples of these standards include The Natural Step, Living Building Challenge, WELL Building Standard, One Planet Living, Planet Mark.


NOW LEASING

The examples from nature. The origin of the ideas can be very diverse; their source can be either built or from the natural environment. The practice of regenerative architecture aims not only to decrease the ecological footprint of buildings but to make it positive, and also to produce architectural creations which foster a healthy lifestyle, and which are socially integrative. To achieve this, it is becoming a widespread practice that examples from nature or natural sciences form the basis of architectural design. One such approach, biomimicry, can be seen as following the best practice of nature, which has developed over millions of years and which is imitated with the help of modern design tools and building technologies by using natural materials and space creation. Buildings and cities can be thus designed the way nature 'designs' its systems, as natural ecosystems are the best models of sustainability. Natural ecosystems evolve to be in balance, and when disrupted, tend to reorganise and regenerate. In contrast with the principles of natural systems, current construction practice has rarely bothered to replace or replenish any of the resources used.

The built examples. From small scale zero cement, net zero carbon buildings such as the Cuerden Valley Park in the UK, to the commercial Bullitt Center in Seattle, to the UN17 Village in Copenhagen, we have buildings demonstrating it is possible. As Denis Hayes, CEO of the Bullitt Foundation, remarked [4], the Bullitt Center (see Figure 4) is about opening a wedge into the future. Once something exists, no one can say it is impossible.

Figure 4
Bullit Centre, Seattle (Courtesy International Living Future Institute)

The data. It is vital to feed simulations and tools with real-world data. There is access to big environmental data. Through the data monitoring of the ecosystem and human relations to design, designers will be able to develop regenerative environments. This will make data one of the most valuable materials for future design practices. This necessarily implies both the recording of data and the use of simulation that learns from these data and forecast behaviours. According to the assertion: *data is not information, information is not knowledge, and knowledge is not wisdom*, data need to be transformed into information by the team of designer and scientist. Further steps are required to turn data into relevant design knowledge; this takes a creative spark. The spark of the invention that can spill out onto the back of a napkin is still crucial, but the complexity of Regenerative Design needs to be supported by digital models that can facilitate the exploitation of Data in design.

The software tools. With sophisticated digital modelling, data and monitoring tools, we have a new world of resources to make designs and planning decisions that are far more informed. Modelling can be used to keep track of how a single design has an impact on the natural world, and how the natural world could inspire design, giving way to new and innovative methods of bringing sustainability into a practice's structure also. These are the foci of the chapter titled *'Tools and Data for Holistic Modelling'*.

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OVERCOMING BARRIERS TO IMPLEMENTING REGENERATIVE DESIGN

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The challenge for design practice is a matter of integrity, of upholding the numerous oaths taken when becoming accredited professionals, and therefore not undertaking design commissions that will continue to contribute to climate change deterioration. Today, we have the economic frameworks, the standards, the software tools and indeed the examples of buildings and facilities that are regenerative. The challenge for design practice is putting these into place, and replicating and improving upon the cases. The title and message of the World Green Build Council's report – *'From Thousands to Billions'* - nails it: We have thousands of buildings that exhibit regenerative characteristics that we need to scale that up to billions. Urgently.

The problem of climate change is strictly linked to human activities on Earth. Despite this awareness and over a decade of strategies and programmes, the progress in the built environment has been barely visible; we still lack action in effectively addressing these global issues.

Although most professionals involved in the built environment sector declare to embrace sustainability as one of the primary drivers of their ethos, regenerative design has been achieved at a disappointingly small scale, and it is hard to find examples. There is a (still limited) number of projects that are intended to be demonstrations of Regenerative Design: The Bullitt Centre, USA; The EAU Enterprise Centre, UK; The UBC CIRS Building, Canada; The Edge, NL; Geelen Counterflow, NL; Snøhetta's Powerhouse Kjørbo, Oslo.

It is necessary to move this practice beyond large commercial flagships. There is more environmental impact – and thus more opportunity – within the long tail of construction, necessitating the myriad millions of small projects across the globe to embrace change [1]. The book hosts several case studies in the chapter titled *'Case Studies of Regenerative Design'*.

BARRIERS AND OPPORTUNITIES OF REGENERATIVE CERTIFICATION

What are the obstacles to putting regenerative design principles into practice? It is not technical feasibility: technical solutions are already available on the market. It is not only the cost premium: even considering an initial investment that is higher than the market average, Regenerative buildings have no bills to pay. Existing policies and regulations represent a barrier. Innovation and new ideas run counter to the conventional, and as a result, people often resist being early adopters.

Efforts can be further hindered by energy and environmental targets legislated under building codes, which in their negotiation between ambitions and market willingness often default to the latter. It is not good enough to rely on legislation or standards to increasingly ramp up towards regenerative building levels. Firstly, because we simply do not have that luxury of time; and secondly, because only designing or building to code or regulation is the least bad one can be without being illegal. Both EU regulations and voluntary certification systems focus on limiting damage to the environment with scarce attention towards regenerative design. As such, they are not great drivers for designers to embrace higher ambitions and for them to upgrade knowledge and tools to face regenerative design challenges.

Although the green building movement has played a crucial role in increasing awareness and providing tools for sustainable design and construction to a community of professionals, manufacturers, developers, owners, public officials and policy owners, the approach to sustainability has been reduced in many cases to tick boxes on a check-list. We have lost sight of the objective, while climate change runs at a speed that is higher than the spread of good sustainability practices.

Instead of a world that is merely a less bad version of the one we currently have; we ask – what does good look like? That is why a new, more systemic, comprehensive and effective approach is sought. One example, the Living Building Challenge (LBC), provides design and construction teams with guidelines on how to integrate the living building concept by relying on a system thinking approach [2] [3]. A ‘Living Building’ is one that is integrated with and mimics natural processes and obtains all necessary resources for operation from the natural environment (rainwater, wind, sunlight and where possible natural materials), and in doing so achieves a net-zero impact on the environment.

THE BUSINESS CASE FOR REGENERATIVE DESIGN

There is a business case for regenerative design. These designs are resilient, self-sufficient systems that provide energy and water security, as well as long-term financial benefits [4] [5]. Are regenerative buildings feasible from an economic and financial standpoint? This is a common concern about the concept of green building in general, but the question is urgent when dealing with regenerative design. Everyone, regardless of economic status, should have access to healthy, safe, and affordable buildings. For instance, the International Living Future Institute (ILFI) collaborated with affordable housing developers who use the LBC Framework for Affordable Housing to design and build homes that have no energy bills, are free from toxic materials, and are truly sustainable for future generations. Here, the key driver was to overcome social, regulatory and financial barriers that currently hinder the application of deep green technologies to affordable housing [6].

It should be noted that regenerative design would require the design team also to advocate and inspire policy officials, utility companies, community leaders and decision makers to replace entrenched and regulatory barriers and implement policy initiatives that ease, rather than frustrate, regenerative buildings. For example, in respect of Living Building Challenge projects, the ILFI provides advocacy tools, a policy leadership toolkit, case studies and reports that facilitate this process [7]. Also, the shift required to implement regenerative design in timely and effective ways needs a change in the mindsets of the stakeholders of the building sector, necessitating a focused collaboration and education at all levels.

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INTEGRATED REGENERATIVE DESIGN

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Due to technological advancement, we have the available tools and methodologies to transform our architectural practice from sustainable to regenerative. However, the lack of knowledge and inefficient coordination between stakeholders are hindering this endeavour. The integrated design process, with its wide application and positive impact in the built environment, can become a reality.

The increasing demand for a regenerative built environment is inevitable. However, only a few real projects exist which fulfil the goal of such a complex issue. To reach global Sustainable Development Goals (UN SDG) [1], the whole design & construction process and value chain must be studied carefully to create more of a positive impact. If the different stakeholder groups of a development and construction project do not understand each other's interests, the idea of increasing the wellbeing and health of our society will remain just a dream.

For instance, in a commercial development project the primary stakeholders, such as the investor (private or public), the developer, the groups of specialists (such as the architects, engineers etc.), the authorities (municipalities, fire department etc.), general contractors, facility managers, inhabitants, the public etc., have different interests. The investor is rarely interested in reducing the utility costs because this requires further investment while less profit can be made. The contractor is involved in cutting down construction costs compared to what was contracted as much as possible. The building inhabitant, who is the most interested in a healthy and effective (water usage, energy usage, etc.) working and living environment, is rarely present at the planning and development phase.

However, high-performance and emerging state of the art buildings, such as projects developed according to the principles of regenerative architecture can be achieved through collaboration and coordination of the aims and work of the different stakeholders. In recent decades, during the development of complex and sustainable buildings, an ever-increasing emphasis has been put on adopting Integrated Design Project (IDP) [2],[3] or Integrated Project Delivery (IPD) [4].

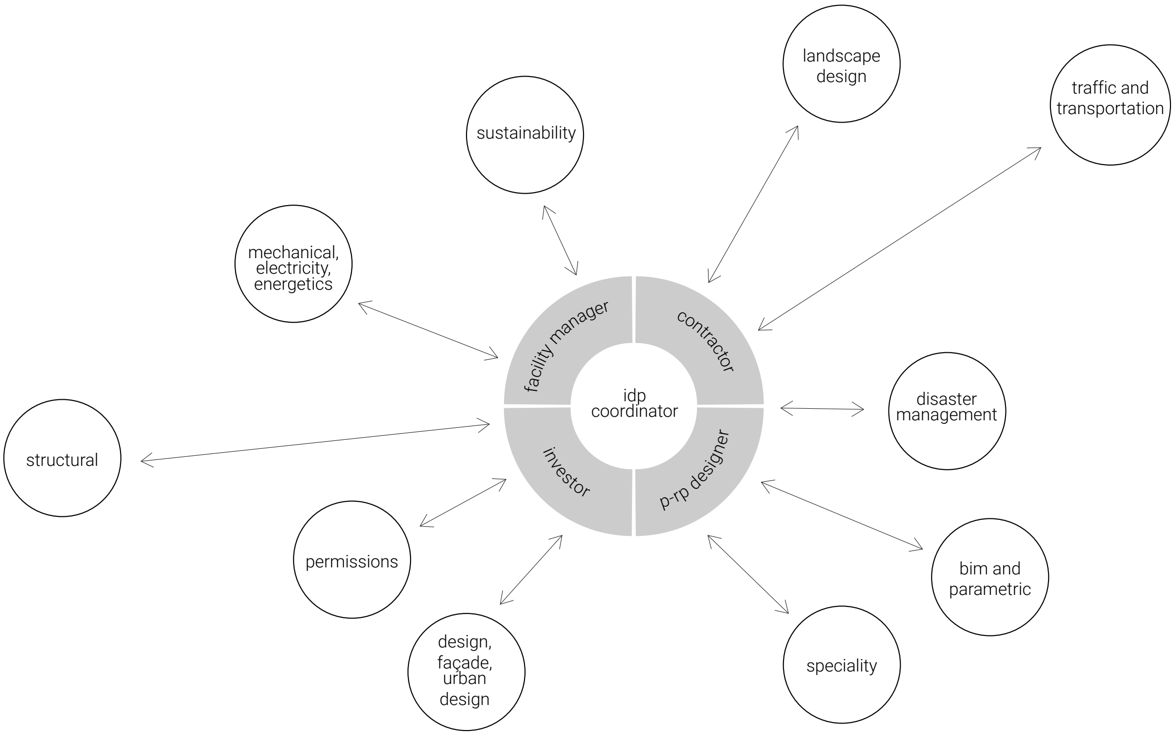

Figure 5

Possible structure and group of stakeholders and the communication of an architectural project (source: Paulinyi-Reith and Partners Architects)

Compared to the traditional planning and development method, which is a linear process, IDP or IPD is a circular project management process (Figure 5). Not only is real-time decision modelling a significant benefit of these integrated processes, so is the deeper involvement of stakeholders from the beginning. Thus, all the participants in value creation are informed about the decisions, and, furthermore, they can influence them. An essential element of this process is that integration from the beginning makes it possible to harmonise the interests and aims of the stakeholder groups.

In the case of regenerative architectural creations, besides the traditionally known participants of the value chain, newer consultants, methods and tools are playing a more significant role in the production of high-performance buildings. Among these new participants, apart from the representatives of the engineering disciplines, there are also those of the social and natural sciences. For many, it has become clear that exclusively engineering solutions cannot respond to the architectural/built environment questions connected to human behaviour, health or well-being [5]. Thanks to this development/planning, teams also include doctors, scientists, sociologists, ecologists etc.

The key to increased adoption of regenerative architectural practice is the appropriate education of stakeholders within the value chain. Many methods and technologies are new or perceived to be new for project stakeholders, and a fear of the new or unknown or a lack of factual knowledge can distort decisions. This can only be resolved by sharing knowledge and best practice.

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BLENDING SCIENCES INTO REGENERATIVE DESIGN PRACTICE

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Architects need to orchestrate the complex task of designing cities and buildings that reverse ecological damage, and enable ecological evolution and reinforce the state of health of inhabitants. Their design should thus regulate climate, provide habitat, cycle nutrients, purify water-air-soil and produce their energy and water. This moves architects to think of design as part of nature, which means studying, understanding and modelling not only buildings but all the natural systems and their inhabitants. While this regenerative approach is attracting growing interest among design practitioners, transitioning from a traditional to a regenerative practice presents challenges.

Architecteure is moving from working on buildings in separation from their context to the design of living systems with co-evolutionary capacity, It is now seeing interrelationships across multiple scientific domains and patterns of change rather than static mono-focused design approaches (e.g. a design that is solely concerned with energy). It is increasingly understood that it is necessary to addresses phenomena in terms of wholeness rather than in terms of parts in order to create new and more meaningful relations.

To imagine solutions for adaptation to climate change, practitioners transfer biological and ecological knowledge into a design context. Looking at plants or animals that are highly adaptable or ones that survive in extreme climates or through climatic changes may provide insights into how buildings and cities could or should function. This requires the study of organisms and ecosystem in terms of forms, materials, construction methods, processes or functions.

Examining the qualities of ecosystems that enable them to be adaptable and resilient is a potential avenue to follow. However, scientists need to join the design team orchestra. We should thus think of regenerative design as an integrated blend of scientific disciplines, including but not limited to ecology, environmental engineering, biology, climatology, agriculture, physics, chemistry, material science, and medicine. Thus, it involves integrating a wide range of factors from the ecosystem level to individual molecules.

REGENERATIVE DESIGN IN ARCHITECTURAL PRACTICE

The fostering of new, meaningful, nature-based relationships requires planning on the front end of the design process for the orchestration of knowledge and the generation and assembling of data in digital models. Below is a list of concepts that are key to the regenerative practice and that are related to the processes of science-based creation.

Mindset. Success in regeneration means to design to evolve and continually develop new potential through interventions in the built environment. Regeneration is a practice philosophy, a design process and a result. This can be derived by the Merriam Webster definitions or regenerate:

- formed or created again
- spiritually reborn or converted
- restored to a better, higher, or more worthy state

A research-based understanding of how a building works and what it strives to contribute to the world. When the global and local dynamics and essence are understood, it becomes possible to design, develop, and plan for the future at a new scientific level. These entail the ability for architectural practice to discern the ecological and the human patterns by accessing big data, scientific data as well as historical records and ancient legends.

Architectural office as an orchestra of scientists and designers. In regenerative design, the design team members include scientists in an orchestra. To enhance the health of the ecological systems climatologists, hydrologists, geologists, ecologists, biologists, material scientists, chemists, physicists, to mention some, need to be involved. It is essential that architects do not act as soloists as often happens in a one-man led company. An orchestra made up of the most excellent soloists will not often perform well together.

Avoid compartmentalised firm structures. The design professions (and indeed, all professional disciplines) have become more specialised and our processes more compartmentalised. This makes them more manageable but tends to lead to solutions where each component in the project is designed to perform at peak effectiveness but sacrifices a systemic approach that, especially for sustainable design, is key to connect in meaningful relations all the layers of ecology, material flows and human health.

Adopt Systemic approaches. Designers optimise the function of the system. Selecting the appropriate components and combining them in the best way for overall performance requires a much more nuanced approach and finer set of tools. It requires an integrated design process involving all relevant scientific disciplines from the beginning. Generally, this multidisciplinary team must work iteratively, circulating the design over and over with scientists and modellers of the various systems until it 'converges' on an optimal solution (optimal for multiple criteria, not just one). The parametric digital tools, as seen later, are essential to the success of this process.

Direct and indirect conncetion - with and of flows. Practice should distinguish between the direct and indirect ways through which buildings engage with resource flows, and then connect them to merge them. Direct involvement includes approaches and strategies that occur within the bounds of the project site. The indirect commitment extends beyond the limits of the site and can thus be implemented o n a much larger scale.

Represent relations among ecosystem, the built and human health. The design needs to happen with an extended type of interactive and multiscale maps. These are global, regional and local beyond the immediate building and site boundaries. Several layers of information need to be represented and modified by design. These can be a representation of natural, materials and human flows. Such maps and diagrams facilitate the broader integration of allied design professionals - urban planners, landscape architects and engineers, together with other disciplines and ecologists, botanists, hydrologists, material producer, doctors, who are typically not in direct dialogue.

Ecological Impact Assessment, Material Flow Analysis and Health Accounting. Compare impacts of design options with numerical evidence and modelling of the ecosystems and humans by using Ecological Impact Assessment, Material Flow Analysis and Health Accounting. This means tracing the environmental impacts of existing and proposed designs. This information determines the most ecological and sound design possibility.

The right design converges several patterns. A right solution is good because it is in harmony with those larger patterns, solves more than one problem, doesn't create new ones, and creates ecosystem capacity while enhancing human health. By combining multiple paths to each end, designers increase the quality of the overall system.

A NEW VOCABULARY WITHIN THE PRACTICE

The move to regenerative approaches has led to the challenges of incorporating new science-based vocabulary in practice. Recurring in regenerative design definitions are themes related to nature, ecosystem, wildlife, living organisms, organic and inorganic matters, physiology and health.

The holistic and profoundly integrated nature of regenerative design is different from the common vocabulary proposed by the checklist of sustainable design rating systems. These lead to achieving credits without a real understanding of ecology and location patterns. Browsing trough the key terminology used in regenerative design related publications helps to track the scientific domains and disciplines that are intgergrated. The paper *'Regenerative Development and Design'* by Pamela Mang and Bill Reed [1] collect the following definitions:

Ecology: the interdisciplinary scientific study of the living situations of organisms in interaction with each other and with the surroundings, organic as well as inorganic [1].

Biomimicry: an emerging design discipline that looks to nature for sustainable design solutions. [2]

Ecological sustainability: based on ecology and living systems principles, focuses on the capacity of ecosystems to maintain their essential functions and processes, and retain their biodiversity in full measure over the long-term [3]

Ecosystem concept: a coherent framework for redesigning landscapes, buildings, cities, and systems of energy, water, food, manufacturing and waste through the effective adaptation to and integration with nature's processes [4].

Locational Patterns: The patterns that depict the distinctive character and potential of a place and provide a dynamic mapping for designing human structures and systems that align with the living systems of a place [1].

Place: the unique, multi-layered network of ecosystems within a geographic region that results from the complex interactions through time of the natural ecology (climate, soil, vegetation, water, wildlife, etc.) and culture (distinctive customs, cultural values, economic activities, traditions, etc.) [5],[6].

The above terms and definitions point to a design process in which the traditional stakeholders - architect, mechanical engineer, contractor, cost estimator, building owner and operator - collaborate closely with scientists to explore how to connect design and operations to the broad ecosystem dynamics, the flow of materials and human health, in a systemic manner.

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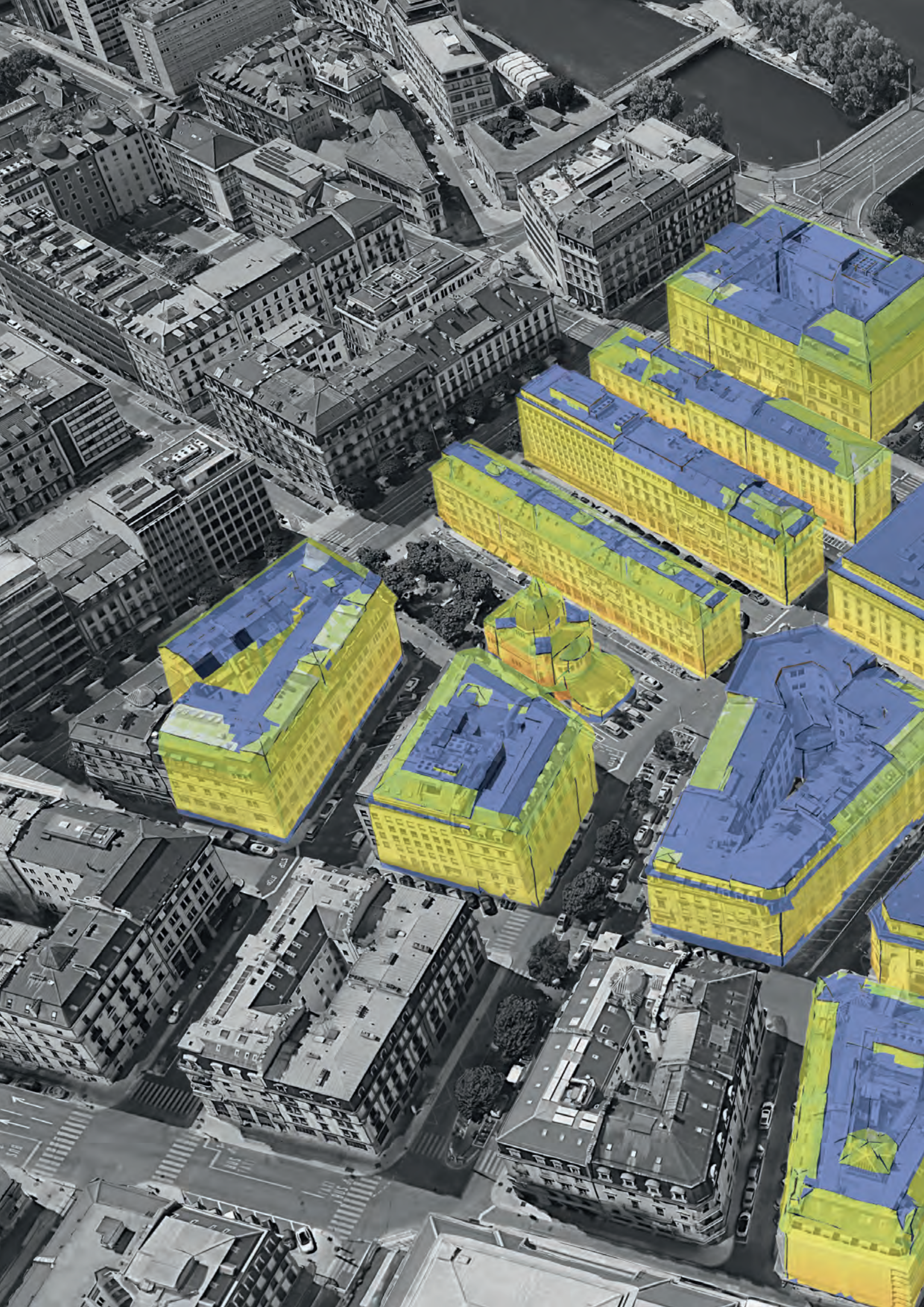

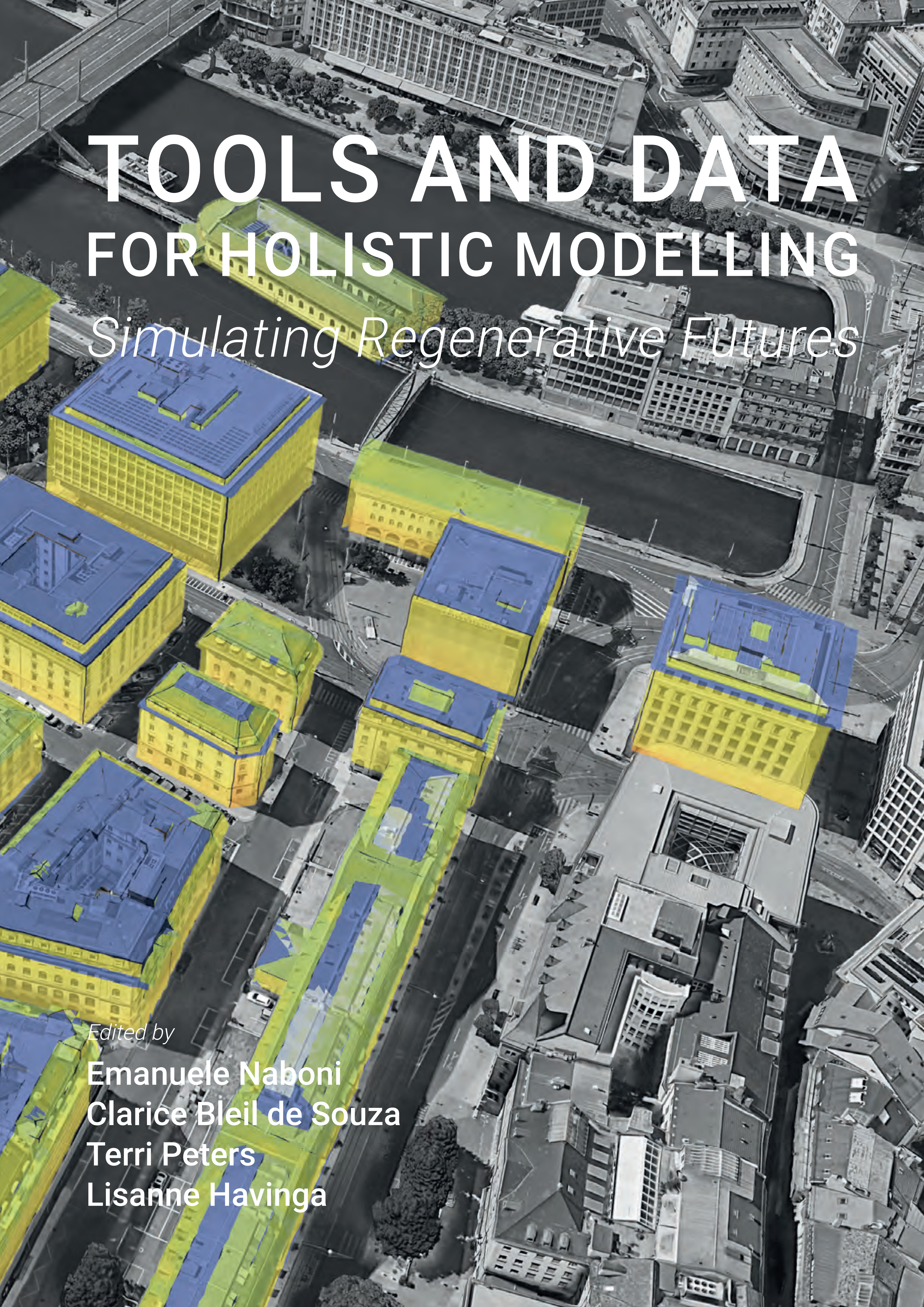

TOOLS AND DATA FOR HOLISTIC MODELLING

Simulating Regenerative Futures

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Chapter Cover Image - Visibility Index, Geneva

Visibility index simulation of the Hollande district in Geneva, Switzerland. Contributions from a set of viewpoints are averaged to get a mean visual amplitude index per mesh face. This may be used to quantify visibility on an objective basis and can be matched with solar energy generation potential for planning purposes

Courtesy Pietro Florio

TOOLS AND DATA FOR HOLISTIC MODELLING

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TOWARDS A PROGRAMMABLE MULTI-DOMAIN DIGITAL DESIGN

Emanuele Naboni *KADK Copenhagen, Denmark*

Regenerative sustainability [1] is a concept relevant to building performance assessment, which argues for design approaches that go beyond mitigating environmental impacts and instead positively impact people and nature. While this is a promising direction for sustainable design, new design tools and workflows need to be developed to put these ideas into practice. Following regenerative design principles, architects can no longer afford to merely reduce the environmental impact of their design solutions. Rather, they should perceive every single project as an opportunity to contribute to the positive development of the context and strive to regenerate the environmental qualities of places.

As the population keeps growing and climate change does not slow, every building should be considered as a dynamic equivalent of an organism that harmoniously gives and takes from the environment. This has encouraged architects, scientists and designers to dig deeper into sciences, from one side by looking at the integration of global big data in design, and from the other by exploring the microscopic levels of natural systems, to derive solutions for architecture. Designing with global, local and nano scales in mind certainly challenges designers to embrace forward thinking and multidisciplinary knowledge. To achieve climate-tuned solutions, enhance users' well-being, and promote biodiversity, architects need to go beyond design prescriptions and rules-of-thumb. Kristoffer Negendahl argues, in his section, for the use of informed multi-domains algorithms and real data, rather than textbook examples and experience from similar projects. He explains how terms such as '*access to direct sunlight*', '*shelter from wind and rain*', '*optimal views*' and '*connectivity to nature*' are now encoded terms in computational models specifically designed to support and enhance the process of design.

This encourages designers to seek open software tools that are programmable to cope with customised and multi-domains issues [2-5]. There is a need for performance simulation methods capable of modelling the integration of ecosystems, buildings and inhabitants. This chapter presents instances of integrated software tools capable of coupling equations that capture the essence of relations of different scientific domains.

FROM ‘SINGLE PROBLEM’ TO HOLISTIC TOOLS

Available simulation tools have been developed to deal with one isolated environmental issue. The explosion of such digital tools for environmental analysis has made it easier than ever to ‘*do less bad*.’ Measuring the damage we do today and reducing that of tomorrow is not yet trivial, but there are countless software packages and metrics available to help [6].

These tools relate to either a building/districts’ energy performance; or the reduction of operational and embodied energy consumption and emissions; or the optimisation of indoor thermal comfort and visual comfort; or the modelling of flows (e.g. water, air) around and inside buildings. Other tools are dedicated to model outdoor thermal comfort and air pollution patterns. More recently, tools are beginning to couple diverse environmental problems in a holistic framework. Most typically, these tools integrate energy simulation, daylighting, and embodied energy calculations. However, as Alexander Jacobsen explains in his section,regenerative design holds designers to a higher standard, and actively improving environmental and human health requires more than an arsenal of tools. Regenerative design requires a vision greater than the classic topics proposed by green certification rating systems.

Regenerative design calls for tools that are open to being customised by users, beyond the typical architectural sciences problems, in order to respond to a set of performance targets such as those linked to the local ecosystem and to human health. To explain the shift, it is no longer conceivable to simply model the impact of design on the ecosystem, or the impact of design on health. In regenerative design, it is necessary to couple models of one or more variables of the ecosystem (e.g. local climate, local water cycles, the behaviour of other species, natural patterns of vegetation growth) and of people (e.g. behaviours, physiology). This further step in the integration of simulation domains and customization of environmental issues is made possible by parametric simulations.

PARAMETRIC REGENERATIVE DESIGN

Parametric design is a process based on algorithmic thinking that enables the expression of parameters and rules that, together, define, encode and clarify the relationships between design intent and design response. It is this relationship that a parametric digital environment is supposed to uncover in order to inform the design and allow it to be optimised quantitatively, and in an iterative manner. New environmental parametric plugins pop up every day, thereby allowing the evaluation of the multi-disciplinary environmental and health related issues of regenerative design.

Theodore Galanos elaborates on this concept in his contribution discussing the opportunity of parametric design when used to produce design solutions that are attuned to the environment by mimicking natural patterns via the use of optimisation techniques.

One of the tools that have gained prominence in the field of parametric simulation is the visual programming tool Grasshopper. Grasshopper is a graphical algorithm editor tightly integrated with Rhino's 3-D modelling tools. Unlike RhinoScript, Grasshopper requires no knowledge of programming or scripting, but still allows designers to build from simple to awe-inspiring solutions. Of all of the available Grasshopper's environmental plugins, Ladybug Tools is among the most comprehensive, connecting Rhino interfaces to validated environmental simulation engines. The Ladybug Tools family of plugins includes Ladybug for climate data, Honeybee for daylighting, energy modelling and thermal modelling, Dragonfly for large-scale climate and urban heat island effects, Butterfly for CFD analysis, and Ironbug for HVAC modelling. As such, Rhino, Grasshopper and Ladybug Tools are interconnected. Rhino defines the geometry of the model, Grasshopper is used to change and optimise this geometry parametrically, and Ladybug tools are used to further evaluate the environmental performance of these geometric iterations. Chris Mackey, the co-developer of Ladybug Tools, discusses in his section how Ladybug Tools are evolving based on the users' needs of dealing with several domains and scales of environmental design. In this chapter, Pietro Florio presents tools that support the assessment of the visual quality of urban elements. Further examples of originally developed plugins that leverage the capabilities of Ladybug Tools are presented in the chapter titled 'Climate and Energy'.

COUPLING ARCHITECTURAL AND NON-ARCHITECTURAL DOMAINS

Grasshopper allows the geometrical co-modelling of urban, natural environments and buildings, which are coupled with equations belonging to the domains of, among others, ecosystems, climatology, material sciences, synthetic biology, biology, botany, human comfort and physiology. With the use of Grasshopper, architects can model a large number of design options by linking problems and performances belonging to various disciplinary domains, enabling the handling of the complexity of environmental issues. The examples included in Terri Peters' section demonstrate the capability of dealing with the multifaceted design problem by discussing some of the approaches of the Danish architectural office 3XN. One example is the Circular House project of 3XN that harvests data at the building component level, generating information that can inform future projects.

Grasshopper also provides access to information on geometries, materials and operations from domains that are not typical to the architectural disciplines. A wide range of regenerative digital design tools is presented in this chapter, including those used to develop strategies for biomimicry, positive energy buildings and the design of green-blue infrastructure. The field of application ranges from the single building to entire parts of the city. As regenerative design continues to evolve, the process is showing itself to be increasingly holistic, but also highly complex. The application of a broad spectrum of plugins representing various disciplines requires the integration of multiple types of knowledge. It is therefore crucial that interdisciplinary pedagogies are implemented to educate software users to make architecture transcend disciplinary boundaries, as explained in the contribution of Clarice Bleil de Souza.

INTEGRATING MEASURED DATA IN SIMULATION

There is a boundless set of unexplored possibilities to integrate Grasshopper Plugins into different regenerative design practices and to appropriately negotiate new design targets. Furthermore, parametric tools allow for the incorporation of measured data (those, for instance, coming from sensors) or sets of climatic data, pollution levels, people's behaviour, or even human physiological data. It is necessary to calibrate and validate simulation models by means of collected data. In this regard, Emanuele Naboni discusses the possibility of integrating big data in design. Also, Dario Cottava exemplifies how smart mobile data and microprocessors could underpin ubiquitous computing (e.g. networking, artificial intelligence and wireless computing) to induce behavioural changes that could co-improve comfort and environmental quality. He presents three projects, taking into account the inhabitants, concerning indoor and outdoor environment behavioural change, while allowing technological devices and computers to vanish into the background. Finally, Dorota Kamrowska-Zaluska and Hanna Obracht-Prondzynska map a series of examples related to the use of Big Data in an urban context.

THE PEDAGOGY OF PARAMETRIC ENVIRONMENTAL SIMULATION

The previous generation of mono-focused tools, which were described above, are ‘black box’ engines. Thus, accessing their code is complicated. As Chris Mackey notes in his contribution to this chapter, ‘*monolithic, isolated tools often hinder the learning process of the modeller and can prevent him or her from reaching a deeper understanding of the underlying components and assumptions of a computer simulation*’. Conversely, Grasshopper is a transparent, open source, and customizable set of python codes. The old generations of tools raise the question of the balance between what tools can offer in terms of education, and what knowledge and competencies designers need to use them [7, 8]. These questions are more straightforwardly answered in the case of parametric tools. The visual programming nature of Grasshopper allows designers to develop their computational literacy: either they understand how inputs, processing and output works, or they will not be able to use the tool. Environmental plugins such as Ladybug Tools, due to their logical, and well-visualised structure, provide a complete understanding of the modelled environmental problem.

BIM FOR RATING SYSTEM COMPLIANCE, PARAMETRIC PLUGINS FOR REGENERATIVE DESIGN IDEATION

It is not possible to talk about software tools for sustainable design without reflecting on how Building Information Modelling (BIM) can be a complementary tool. There is a fundamental distinction between BIM software tools and Grasshopper for Rhino and its plugins. BIM implies the creation of detailed 3D geometries and a very significant amount of data information. BIM is functional for final phases of design, when the analysis of large datasets, such as those of LCA calculations, is required. Rhino is a free-form tool that can work with fewer details, and Grasshopper can be applied to models that are less data-rich, which makes it suitable also for the early phase of design development.

BIM configuration enables the connection with one type of building performance simulation tool at a time such as energy, daylighting and LCA tools. This can be useful when a project is crystallised in its construction details, and the compliance with the rating system such as LEED needs to be proven. BIM has several semi-automated processes for rating system certification. Conversely, parametric visual programming tools enable different performance assessment methods to be customised and connected with an ever-evolving building geometry. The designer can tailor new sets of broad, holistic regenerative design targets by programming and linking new sets of relationships to simulation engines or an entirely new set of equations.

This opens new possibilities not only to explore integrated regenerative performance but also to mimic and find inspiration in existing natural systems and processes (biomimicry and biophilia), which can be described in a new set of relationships. Recently, artificial intelligence and machine learning techniques have been integrated into the Grasshopper environment, allowing for a design that follows the logic of living organisms: the principles of biological evolution can apply. With Grasshopper, the tool then becomes part of the methodology that frames aspirational goals, guides innovation and encourages ideation.

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COMPUTING THE ENVIRONMENT

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Designers are grappling with the challenges of designing regenerative buildings, but it is difficult to know where to start. As Sobek states: *'We lack even basic things like data calculation methods and basic knowledge about sustainable building design… We have no methods for the design and construction of truly recyclable buildings… The list of missing knowledge is long'* [1]. Nevertheless, some offices are treating these challenges as creative opportunities. Three examples by the Danish architecture office 3XN and their research and design team GXN are presented: first, a full-scale demonstration project, Circular House, which uses data and digital design tools to enable building components to be more easily recycled; second, examples of early-stage design simulation work on Swedbank office headquarters, which provided feedback about the performance of spaces before its construction; and third, the ongoing environmental monitoring project at Green Solution House, which collects and visualizes data about the building in use to offer insights about how people use space.

BETTER USE OF DATA – DESIGN FOR DISASSEMBLY

Regenerative design can be defined as enabling social and ecological systems to maintain a healthy state and evolve [2], and within this approach, designers must not only search for the potential to minimise the adverse impacts of designs but must also focus on positive impacts that buildings can have on the well-being of people and the natural environment. These requirements mean that better software tools and digital workflows are needed to simulate and evaluate early stage design decisions to enable feedback into the design process. There is also a creative possibility: the development of new digital tools and methods of simulating can lead to new and improved kinds of architecture that can be longer lasting. For example, Danish architecture office 3XN and their research and design team GXN have developed a full-scale demonstration project using data and digital design tools to enable building components to be more easily recycled, thereby providing designers with a greater range of options and facilitating the move towards a circular economy for buildings [3].

Their Circular House project, in close collaboration with concrete fabricator Consolis, uses prefabricated concrete elements that are embedded with electronic chips that contain data about their production specifications, use, and maintenance (see Figure 1). It is hoped that this information will enable the components to be more easily and accurately maintained and reused [4]. The goal of the project is to more effectively share and use building design data beyond construction, making it useful at later stages of the product lifecycle. This kind of thinking is needed in the construction industry, and proof of concept projects like this could convince other designers to also adopt this method.

SIMULATING EXPERIENCE

Simulation is not new in architecture. Brunelleschi invented a linear perspective to simulate the perception of space, Antoni Gaudí used graphic statics to simulate structural performance, and Pierre Patte used ray diagrams to simulate sound [5]. Architects have long been interested in simulating the experiences of their designs, but digital simulation tools offer more sophisticated and precise options for computing performance, including sound, light and airflow [5].

Figure 1

Prefabricated Concrete for Design for Disassembly, Circular House 2018, GXN/3XN. The particular components are embedded with trackers that provide information about the component's fabrication specifications, use, and maintenance for future reuse. Photo credit Consolis. Courtesy GXN.

The tools are designed to make these calculations and feedback possible, but these workflows remain outside mainstream practice. '*We live in an era where data is abundant, yet very little of this data is used to effectively inform the early design of buildings... early geometries are rarely compared for energy use, daylighting, shading, or airflow potential, since there are many other issues for architects to consider*' [6]. In the last five years, there has been an explosion in digital tools that designers can use, and many offices, including 3XN have developed in-house research teams that provide ongoing support and advanced simulation to design teams. Anderson's comment above from 2014 remains valid, but things are changing rapidly. How long until it does become standard practice for designers to routinely compare early geometries for energy use, daylighting, airflow? How can the profession make this shift?

VISUALISING DESIGN IMPACTS: NEW WAYS OF MONITORING PERFORMANCE

A concept that needs further exploration in the design of regenerative buildings is the monitoring of on-site conditions and comparison to design intentions. Collecting data about the building in use over time is not an industry standard, but some forward-thinking practices are engaging with this process. GXN (the research group of 3XN) and Autodesk Research are carrying out ongoing monitoring of the 3XN-designed Green Solution House project in Bornholm, Denmark [7]. Their Smart Room Collective monitoring (see Figure 2) is designed to allow guests to visualise the impacts of their use of the building and to see real-time building performance data relating to energy, light, air and water use. This idea of visualising resource use is key to helping people understand their impact, and for designers to use this as feedback in the design process.

Figure 2

Visualisation of Smart Room Collective monitoring, Green Solution House, Denmark, 2013, 3XN/GXN. The dashboard shows real-time monitoring of the building's resource use so that occupants can gain feedback about how their behaviours impact resource use. Courtesy GXN.

Figure 3

Daylight Factor Analysis of Swedbank office building. GXN/3XN. This feedback about the predicted performance of the spaces was useful in the early stage design process. Courtesy GXN.

Visualising and making design decisions easier to understand is critical for communication between designers and clients, and parametric tools are proving useful in the design process. Rather than relying on spreadsheets of data, 3XN is one of many design offices that routinely simulates daylight performance, and that has found ways to visualise and use the visualisations of metrics that are difficult to understand (see Figure 3 and Figure 4). For example, when presented with a spreadsheet, clients and designers will rarely know what numbers would be appropriate for annual calculations of annual solar radiation on a façade. It is difficult for designers to gain an intuition of what these might be like, and also challenging to resolve daylight at the unit level versus the overall geometry without graphic visualisation.

NEW WORKFLOWS FOR REGENERATIVE DESIGN

Reflecting on Werner Sobek's statement that a large part of the problem with sustainable architecture is the lack of information and tools, it is easy to understand that the challenges are complex and cross disciplinary boundaries. Sobek's office designed the House B10, a fully recyclable home that was industrially fabricated within a few months and assembled on site in one day [8]. It has predictive self-learning building controls, generates double the energy that it uses, and the surplus energy powers two electric cars and the neighbouring house (incidentally designed by Le Corbusier and now in the Weissenhof Museum). House B10 is the link between the user, the building and the smart grid. Sobek figured out how to build it despite the 'missing knowledge', and yet somehow this prototype has not been replicated.

Figure 4

Swedbank office building, 2014, 3XN. A leading architectural and environmental feature of the building is the ample daylight in all workspaces. Courtesy GXN.

Why are there not more houses like this? The issue of how to advance building methods and cultures is not just related to architects and designers but also to the larger building industry and its culture. Marketing sustainability needs to go beyond 'green' and consider how regenerative approaches will improve people's experiences and quality of life. Regenerative approaches should emphasise *'a co-evolutionary, partnered relationship between humans and the natural environment, rather than a managerial one that builds, rather than diminishes, social and natural capitals'* [9]. Advances in regenerative design require more than just new tools and better workflows, but these are a good start. To productively 'compute the environment', there needs to be a way for designers to better interpret building performance data, to harvest collective intelligence and to share insights across projects. A better understanding of the relationships between design intent and building performance in use would be highly beneficial in order to make better predictions on the journey towards more regenerative buildings that will last generations.

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THE COMPUTATIONAL DESIGN PROCESS

Kristoffer Negendahl *DTU and Bjarke Ingels Group (BIG), Denmark*

Algorithms and pure data, rather than textbook examples and experience of similar projects, today increasingly inform urban design choices. Terms such as '*access to direct sunlight*', '*shelter from wind and rain*', '*optimal views*' and '*connectivity to important points of interest*' are now encoded terms in computational models specifically designed to support and enhance the process of urban design.

The simulation software and even the hardware in supercomputers are now something practitioners build themselves. The models are constructed to resemble (impending) reality and are based on thousands of people-hours in development time and are built on the shoulders of countless brilliant people, thanks to an open source philosophy that provides easy access to knowhow. As a result, we can now perform complex CFD analysis of wind and rain, use space syntax metrics combined with agent-based model statistics and run dynamic thermal models in parallel on clusters in-house, all of which have never been seen on this scale before. Some computational models need increasing amounts of computing power (e.g. CFD an example shown in Figure 11 and Network analysis), and some just need to be refactored and repurposed from existing analytical functions, such as seen in the example use of Manning equations [1] in Figure 5.

TACIT KNOWLEDGE

Does this progress mean we are generating a better design for climate adaptation? No, not automatically! The computational process may direct design choices, or it may only discourage certain bold/bad choices. Regardless of the effect, the intent of the active use in computational modelling means increased awareness of climate adaptation performance in practice. What is certain is that the computational process enhances the understanding of design choices. However, increased awareness and understanding does not mean improved buildings better fit for climate adaptation. What comes before the analysis is what generates adoption for the extreme and changing environment. It is the things unsaid, or in other words, the tacit knowledge, that defines our willingness to go beyond traditional solutions.

The tacit knowledge is the kind of knowledge that can be understood without computational analysis, but to be fully efficient in use, implementation and for further communication, it needs confirmation or disapproval through analysis (see Figure 6). It includes the reason to pursue the analyses, simply because of the doubt that lies in the design choice, but more importantly it also includes a more fundamental standpoint; that climate adaptation is needed for our societies to survive global climatic changes. This level of knowledge is still far greater than the computed equivalent.

The tacit knowledge indeed directs the process of computation. Crucial realisations happen when tacit knowledge is either confirmed or disproved by the computational process, but innovative concepts arise when new tacit knowledge is gained through computation. To structure the use of computation it is particularly useful to combine computation and design experiments when the idea is formulated as a hypothesis. When this happens, as in well-established scientific methodology, we can either compute a confirmation or disprove the idea.

Figure 5

A typical output from the implementation of the algorithms to the design team. Here showing a version of the Manning equations

Figure 7

Sometimes meaningful data is condensed into a risk assessment. In this case, an implementation of the physical motion of rain from [2] transformed into the relationship of a particular depth of the boxes comprising the Bjarke Ingels' Serpentine Gallery Pavilion 2016.

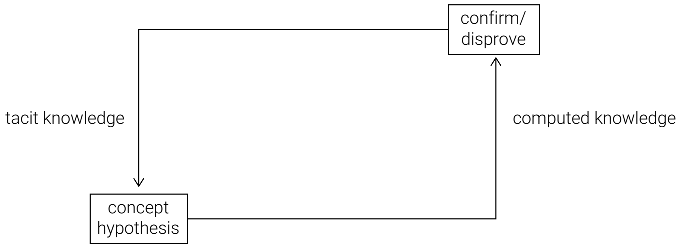
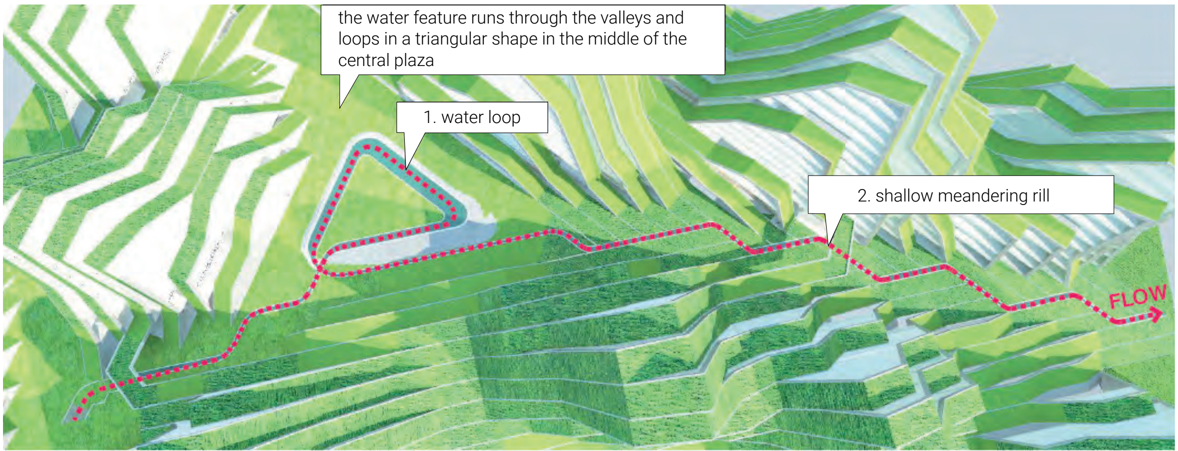


Figure 6

The computational process at BIG, showing the deep connection to the information that can and cannot be computed



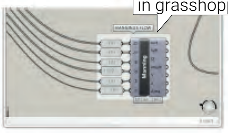
the water feature runs through the valleys and loops in a triangular shape in the middle of the central plaza

1. water loop

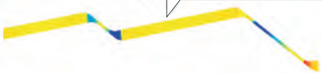
2. shallow meandering rill

mannings formula calculates the flow Q in channels

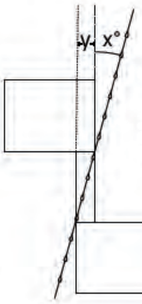
$$Q = = 0.743\cdot\sqrt{S}\cdot Zl\cdot d^2\cdot\frac{\left(\frac{A}{(Zl^2+1)^{\frac{1}{2}}\cdot d+(Zr^2+1)^{\frac{1}{2}}\cdot d+B}\right)^{\frac{2}{3}}}{n}i+0.743\cdot\sqrt{S}\cdot Zr\cdot d^2\cdot\frac{\left(\frac{A}{(Zl^2+1)^{\frac{1}{2}}\cdot d+(Zr^2+1)^{\frac{1}{2}}\cdot d+B}\right)^{\frac{2}{3}}}{n}i+1.486\cdot B\cdot\sqrt{S}\cdot d\cdot\frac{\left(\frac{A}{(Zl^2+1)^{0.5}\cdot d+(Zr^2+1)^{\frac{1}{2}}\cdot d+B}\right)^{\frac{2}{3}}}{n}i$$



the formulas are implemented in grasshopper...



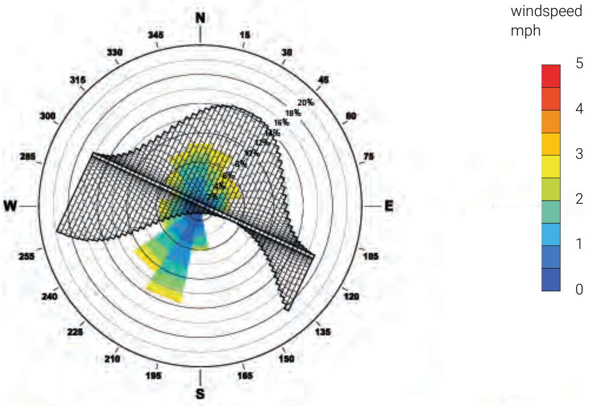
...and visualised in real time in rhino



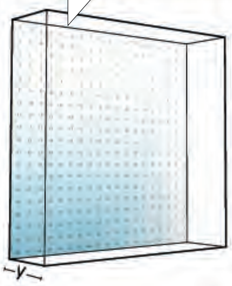
weather data for london is used as input for wind speed, direction and temperature for the summer months the pavilion in use.

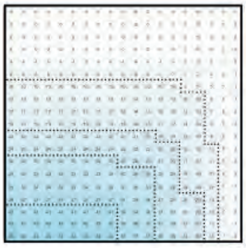
$$m\frac{d^2y}{dt^2} = 6\pi\mu r(V - \frac{dy}{dt})\frac{C_dR}{24} - mg(1 - \frac{\rho_a}{\rho_w})$$

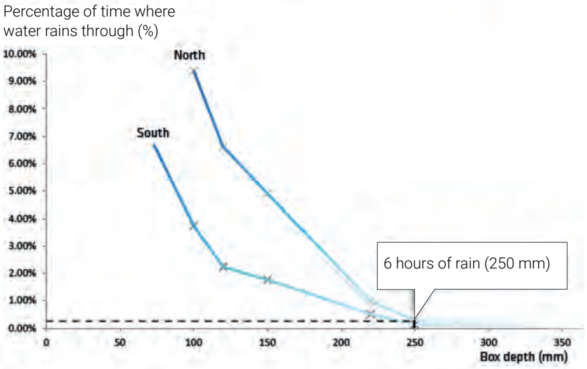
where r is the radius of the droplet; μ is the air viscosity; ρ_a is the air density; ρ_w is the water density; U is the x-component wind velocity, V is the y-component wind velocity; W is the z-component wind velocity, $m=4/3\pi r^3\rho_w$ is the mass of rain droplet, and the Reynolds number is based on the relative velocity. C_d is the drag coefficient on the rain droplet. Drag coefficient on falling water droplet had been measured and studied by Gunn[1949] and the result (expressed as a function of the Reynolds number) is used in the present study.



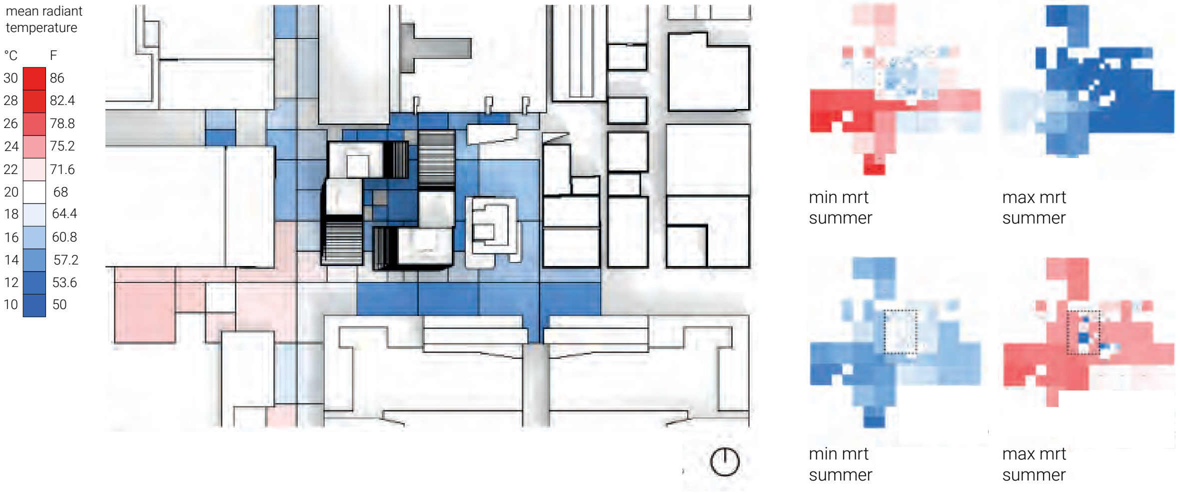
a parametric setup is made to test needed box overlap to avoid driving rain inside the pavilion, the tests will be made using the two facade orientations (nne and ssw)

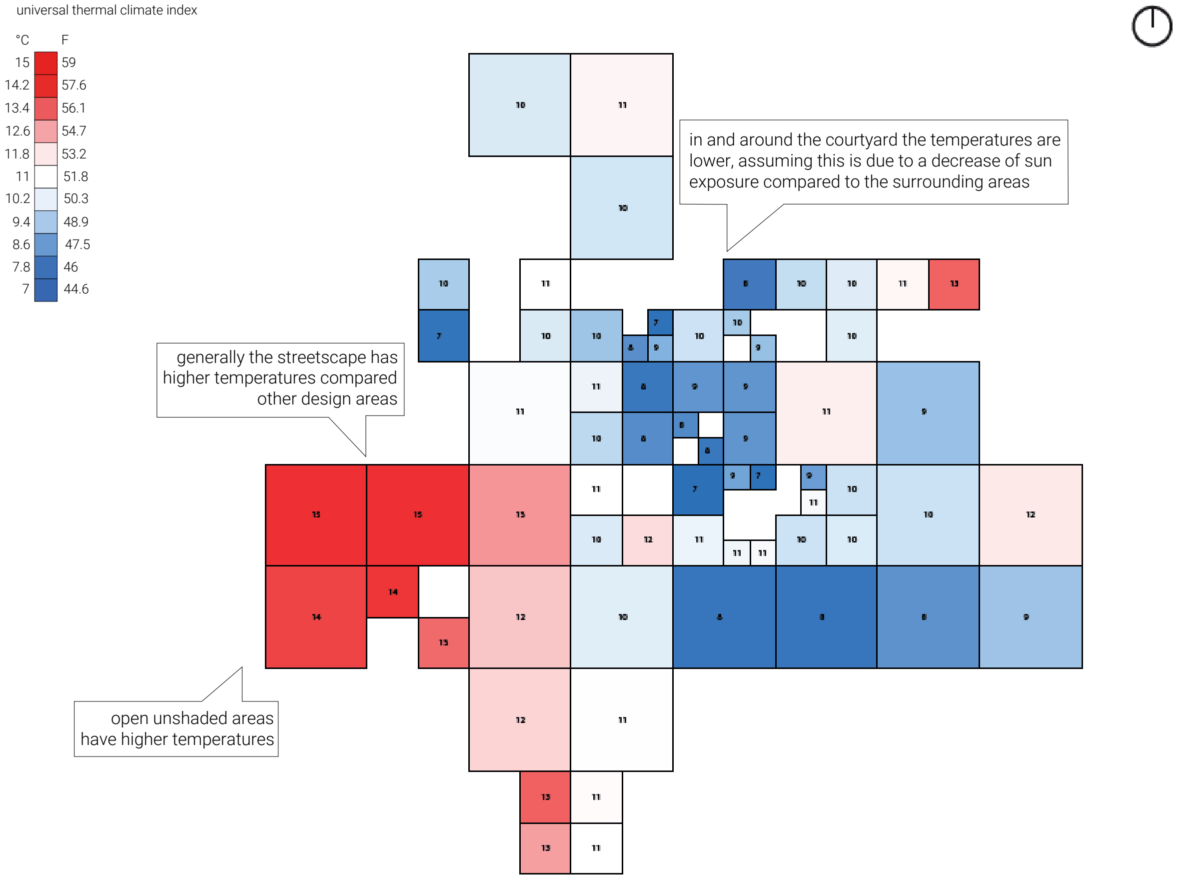






6 hours of rain (250 mm)





in and around the courtyard the temperatures are lower, assuming this is due to a decrease of sun exposure compared to the surrounding areas

generally the streetscape has higher temperatures compared other design areas

open unshaded areas have higher temperatures

Figure 8

Analyses sometimes need to be both spatial and time-spatial. Sometimes it is relevant to debate the scenarios in the context of extreme outliers, sometimes about the mean/median conditions.

The steps are as follows:

- Collect data: Data associated with climate, weather and local site are useful on multiple scales. Specific data such as precipitation and rainfall events as seen in the analysis and design for the Serpentine gallery 2016 –Figure 7, can be useful for very specific analyses.
- Negotiate design targets: Design targets should be deeper founded than local building codes, and arguably more ambitious than most political ambitions.
- Formulate criteria: Meaningful analysis can only be performed if clear criteria are defined.
- Simulate/analyse/synthesise: Simulations tend to be the simpler and less time-consuming task of the three. The analysis typically handles a single criterion, where the synthesis handles multiple criteria. This may be a superimposed analysis or condensed into more complex metrics as shown in Figure 8 and Figure 9.
- Produce condensed conclusions of consequences: Ideally, these conclusions should be available for the entire design team to share, present and communicate further to the client.

Figure 9

Comments on the analysis are crucial to communicating the right conclusions. The comments enhance the design team's awareness of specific areas or elements of the analysis.

ACCURACY ≠ OBJECTIVITY

The challenge of representing urban complexity in a model with meaningful data, and transforming this into a useful tool for the designer, has been a concern for more than two and a half centuries [3]. However, still, now, the lack of data and accessible city models may prevent designers and analysts from obtaining sufficient conclusions. Tools may be plentiful, but they are often hard to master and rarely designed to support a fast and changing design process. Access to unbiased and high-quality data is a further problem, as no tools are specifically made to ensure data validity. When the data grows in scale, for instance, in a machine learning context, the bias of the data becomes an increasingly more significant concern [4]. As for bias, this problem has received much attention in the media and is framed as a problem in the emergent use of artificial intelligence (AI). As such, data inherently comes with a bias, imposed by purpose or just because of a limited methodology of the data gathering process. The whole idea of obtaining statistically valid data is to collect and analyse as much of it as possible and then draw conclusions about behaviour, trends, or whatever else is nested in the patterns of the data. The real issue of data bias '*isn't technical or even managerial—it's philosophical*' [5]; thus, it is related to human nature and challenging to eliminate.

Data-driven decision-making is considered a smart move, but it can be costly or dangerous when something that appears to be true is not true. Even with the best of intentions, there is a high risk of getting results because the data is biased, or the humans collecting and analysing data are biased, or both.

comfort per year

🟥	above 30°C	8.9%	782	hours
🟧	20°C to 30°C	59.1%	5180	hours
🟨	10°C to 20°C	31.8%	2784	hours
🟦	0°C to 10°C	0.2%	14	hours
🟦	below 0°C	0.0%	0	hours

QUALITY OF DATA

Quality of data is difficult to define, as data typically do not have confidence levels and uncertainties clearly defined. Quality of data is thus a function of intangible properties such as 'completeness' and 'consistency' [6]. Increased use of geographical models layered with miscellaneous information as a decision-support tool lends to the realisation of the potentially damaging effects of using weak quality data [7]. Despite these concerns, the computational path to urban climate modelling is taking off in the practices of the AEC industry at a rapid rate. We may argue that our models are objective, and we, as an industry, want to position the use of these urban models as objective science, which always produces the best delineations of reality. However, we must not forget that the objectivity is based on the data chosen to begin with.

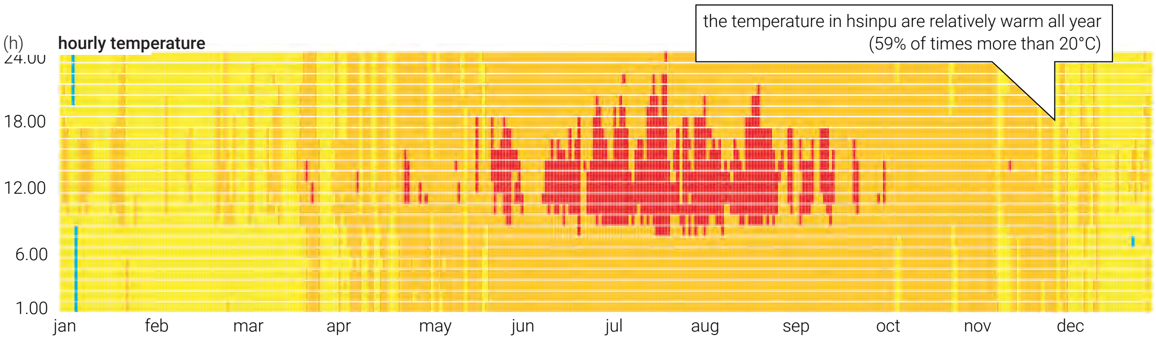
universal thermal climate index

🟥	above 46°C	0.0%	0	hours
🟧	38°C to 46°C	3.4%	299	hours
🟧	32°C to 38°C	29.3%	2562	hours
🟨	26°C to 32°C	22.4%	1963	hours
⬜	9°C to 26°C	44.1%	3862	hours
🟩	9°C to 0°C	0.8%	74	hours
🟪	0°C to -13°C	0.0%	0	hours
🟪	-13°C to -27°C	0.0%	0	hours
🟦	-27°C to -40°C	0.0%	0	hours
🟦	below -40°C	0.0%	0	hours

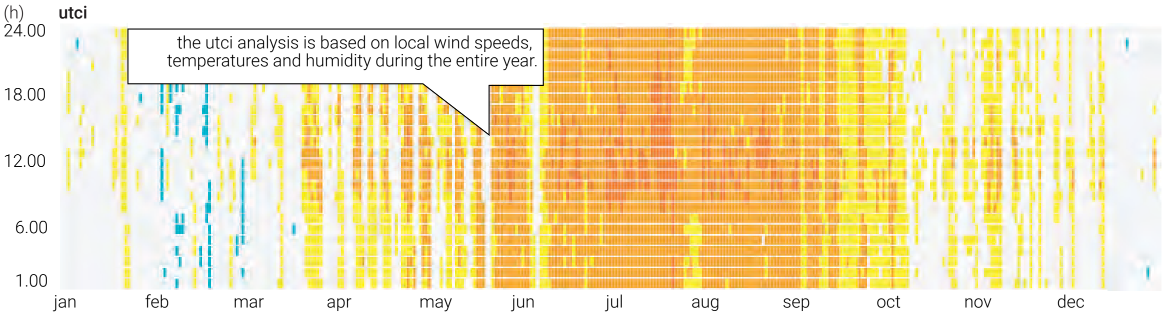
The uncertainties of data leave us in a position where our analysis can inform critical decisions without anyone knowing if the data is flawed. As such, analysis needs to be presented transparently and should be used with a particular criticality and care, and all analyses should be followed by open descriptions of methodology and data sources (see Figure 10 and Figure 11). Unfortunately, this obvious proclamation has yet to be followed by the entire practice. To be transparent, any presentation of any analysis, synthesis or simply visualisation of data must have:

- a clearly defined annotation of all illustrations
- referenced sources, preferably open sourced data
- method of how the data is shown/visualised, and finally
- the tools used to generate the data.

These may seem obvious steps in any scientific paper, but the reality is that practice (and unfortunately in academia as well) has a bad habit of neglecting the details of presenting data. In a sense, the open source framework of data analysis is what the designers of the built environment and the various stakeholders need.



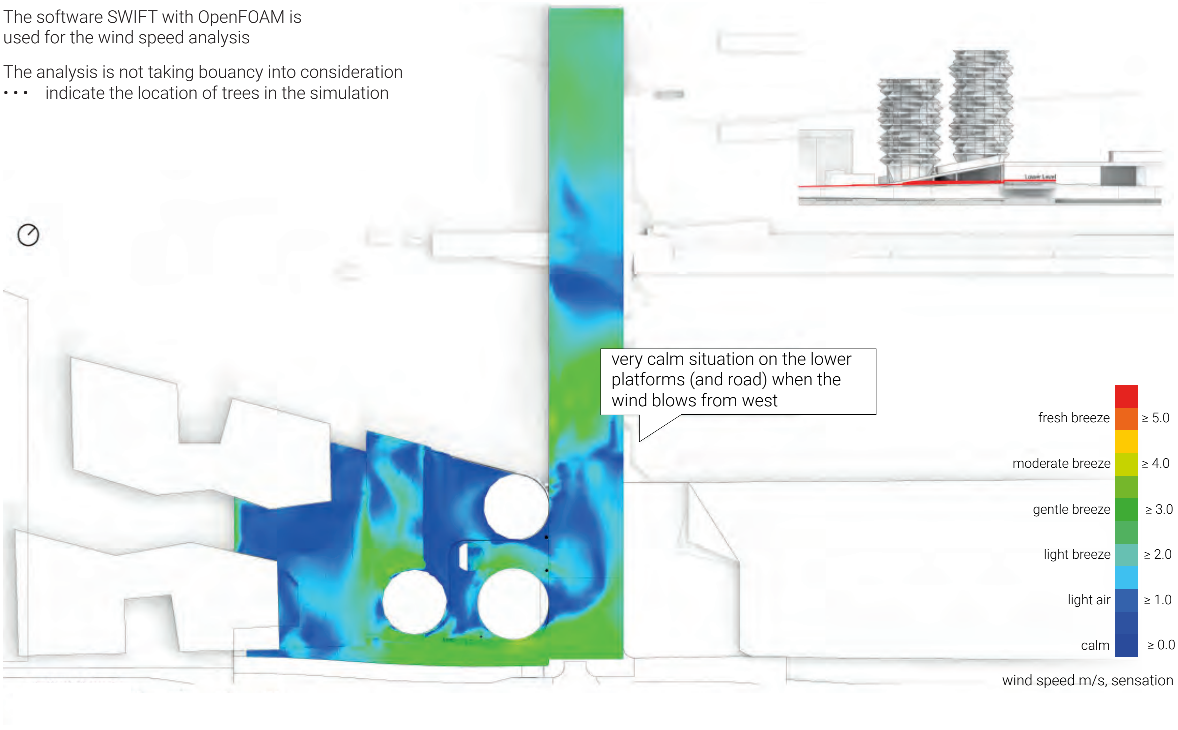
the temperature in hsinpu are relatively warm all year (59% of times more than 20°C)



the utci analysis is based on local wind speeds, temperatures and humidity during the entire year.

Figure 10

Data is the source of our analysis. Therefore, it is important to rely on the quality and access to unbiased data. Here the data is taken from an epw file provided by the U.S. Department of Energy [8] and visualised with Ladybug tools [9]



The software SWIFT with OpenFOAM is used for the wind speed analysis

The analysis is not taking bouancy into consideration
• • • indicate the location of trees in the simulation

very calm situation on the lower platforms (and road) when the wind blows from west

Figure 11

Illustrations often have to show additional context for the designer to have a good way to compare the results. Notice the legend, notation of orientation and the description of methods and tools that have been used to create the analysis. Being transparent as an industry when presenting data and the method is necessary when debating the bigger design choices.

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BIG DATA IN REGENERATIVE DESIGN

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The volume of data in the world is exponentially increasing. By some estimates, 90% of the data has been created in the last two years, and it is projected to increase by 40% annually [1]. Data is growing because the world's capacity for storing information has roughly doubled every 40 months since the 1980s, and because it is increasingly being gathered by inexpensive and widespread information-sensing. A large share of this output is 'data exhaust,' or passively collected data deriving from everyday interactions with digital products or services, including mobile phones, credit cards, and social media.

The rising awareness of ecosystem imbalances and unexpected climatological phenomena implies the need to revise design processes so that the abundant availability of data has the potential to make architecture more site-specific and related to its regional and ecological relevance. As design addresses scientific issues such as climate change, biodiversity, material flows and human health, big data is necessary to promote evidence-based solutions. By reducing the uncertainties of the relevance and the effectiveness of regenerative design, data eliminates the designer bias in selecting options.

Furthermore, with climate and health issues becoming increasingly severe, designers will need to deliver more than drawing sets and poetic visions, and deliver analytical explanations to public authorities of how their designs promote the ecosystems' quality and respond to climate change, as well as provide evidence of the positive impact on the wellbeing and the health of their occupants. In other words, designs will need to be data-rich and this data must be used to justify design strategies. The past practice of the architects that largely relied on guesswork when relating their designs to sustainability [2] must be abandoned. Big data finally allows for evidence-based design.

FROM DATA COLLECTION TO DESIGN CREATION

A comprehensive understanding of the local 'boundary conditions' is a prerequisite for regenerative design. In any environment, natural or built; at the city level and the building level, designers can now use the latest sensor technology and adopt real-time reporting of environmental quality data.

A handful of designers already use large data sets to design architectures that locally deal with global issues. However, the potential of data in design is yet unexplored. Understanding that data is one of the most valuable 'building materials' is an important realisation, and if architects are to harness data from the built environment, significant changes in the design process may be coming. A possible design process that integrates data to address Regenerative Design is framed here.

Access Data. Big data is inevitable in an ever increasingly digitised world. Its use emerged in the past decade, and it is now responsible for a growing number of solutions in areas such as the environment, health, retail and transport. For instance, pollutants that are present in the atmosphere are tracked in the global context via a network of sensors and satellites images, and the global movements of materials and goods can be represented at any level of detail in both linear and circular process. Densely connected 'smart cities' are becoming prominent and are no longer a future outlook. In several of these case, data can be downloaded and are accessible to the public.

Collect data with Crowd Sources. A significant amount of data is not always available or not locally specific. When environmental data come from institutional research centres, they do not always have enough resources to keep the data updated. In other cases, the project site may be located in an isolated area, away from population centres or airports, positions for which it is not possible to obtain data. In all these cases, it is necessary that the design team produces its dataset. Designers can today access crowd sources. These are inputs such as communications and social media feeds combined with position data (geolocalization) to create maps that are always up-to-date with real-time information. Originally, crowdsourcing was used in events such as wars, humanitarian crises, crime, elections, or natural disasters, when critical data accessibility was vital [3]. However, these free and open-source platforms have now spread and allow anyone to start their crowd mapping projects, some of which provide increasingly useful information to designers.

Create your data. Tools for measuring or monitoring environmental parameters, material movements and vital human signs have become very capable and much cheaper due to the increase of advanced technologies. Inexpensive sensors, such as those based on Raspberry Pi or Arduino, enable deployment of sensor technology on a large scale. Sensors operate in real time and producie big data. Therefore, sensors are customarily connected to some units that monitor changes and forward information at regular intervals. When it comes to people, affordable sensors allow measuring environmental quality as an indicator of health

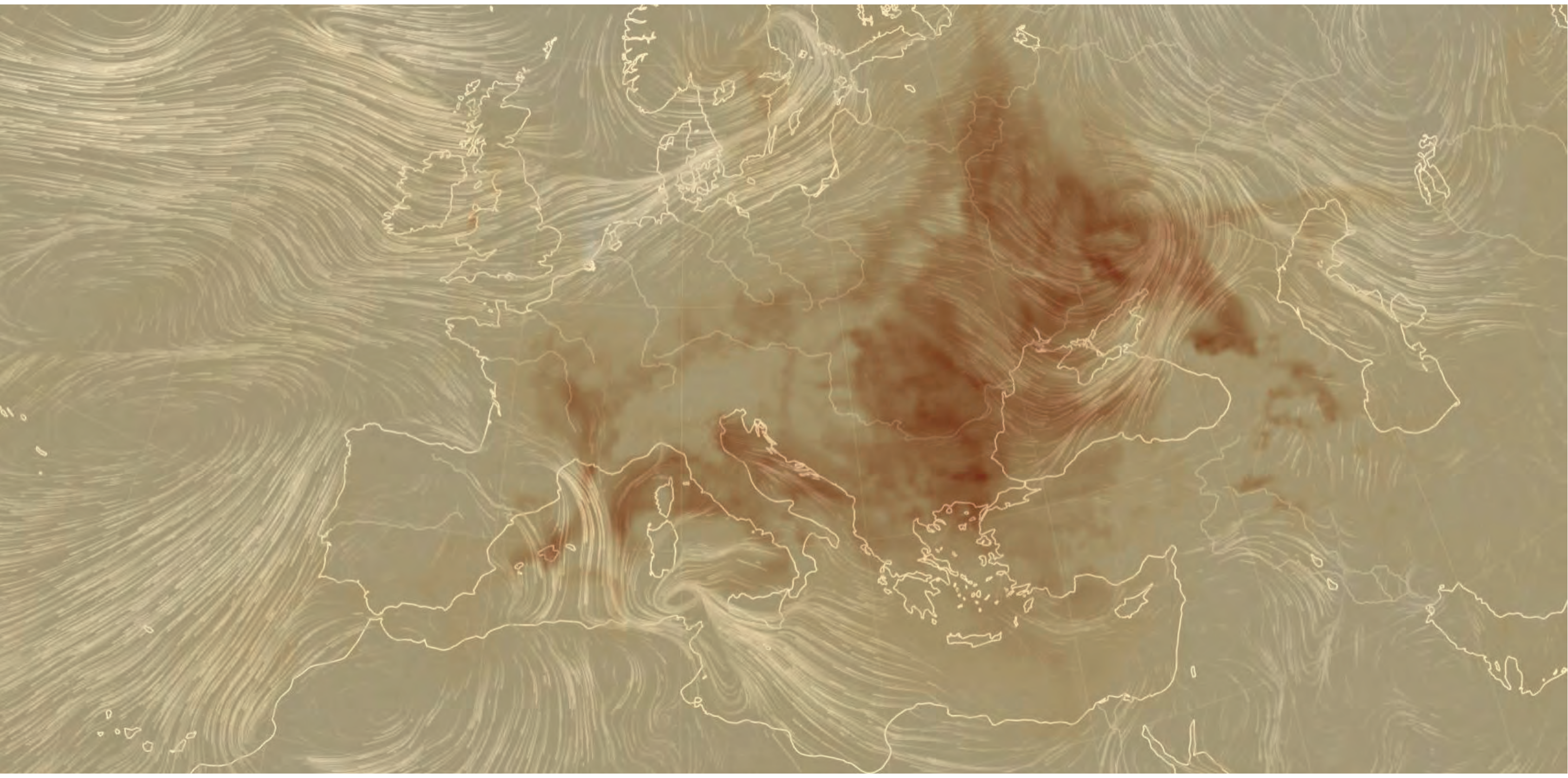


Figure 12

The concentration of CO_2, using supercomputers, Earth Null School forecasts weather and pollution patterns updating the weather map every 3 hours (Source: [10])

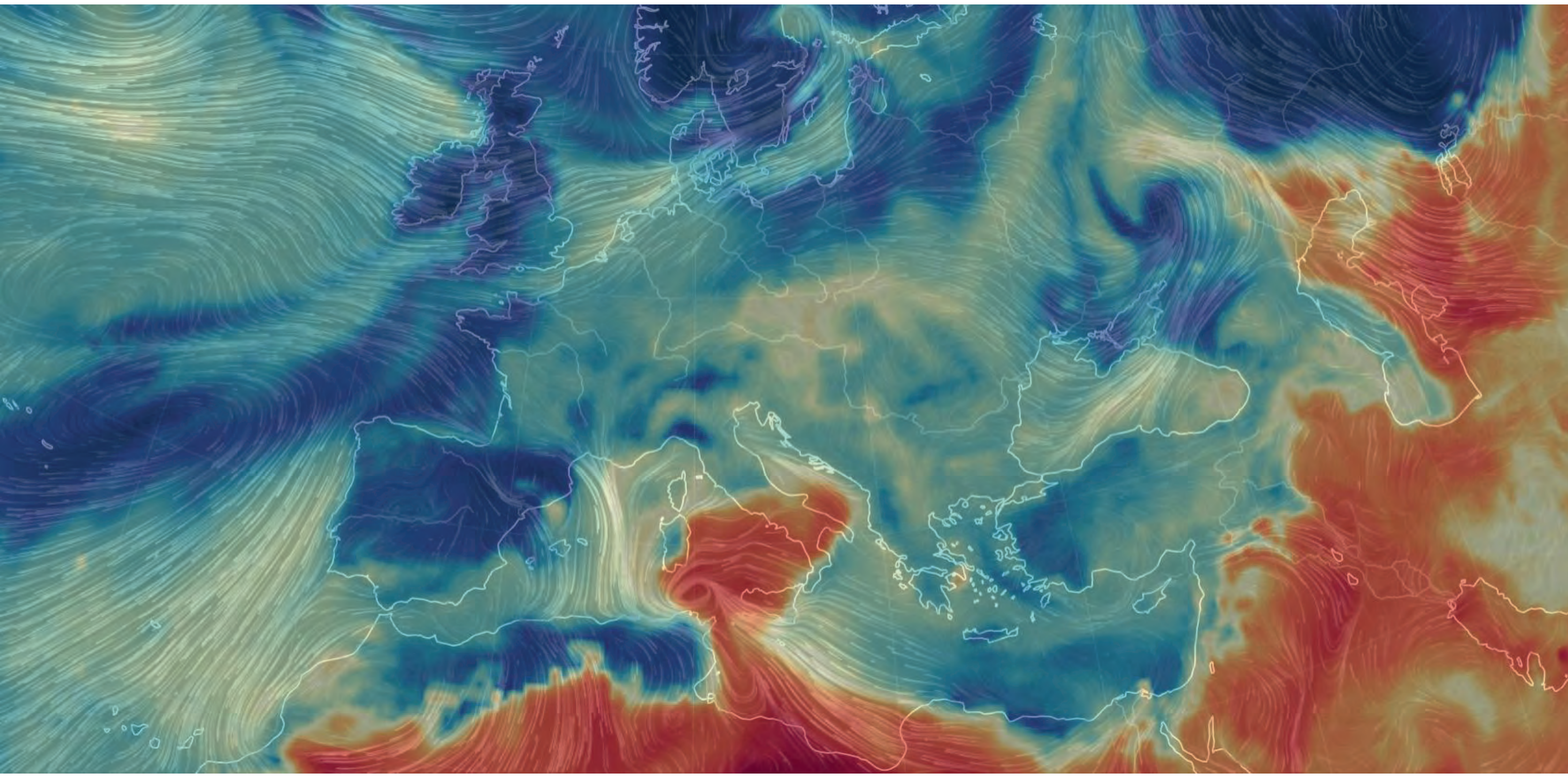


Figure 13

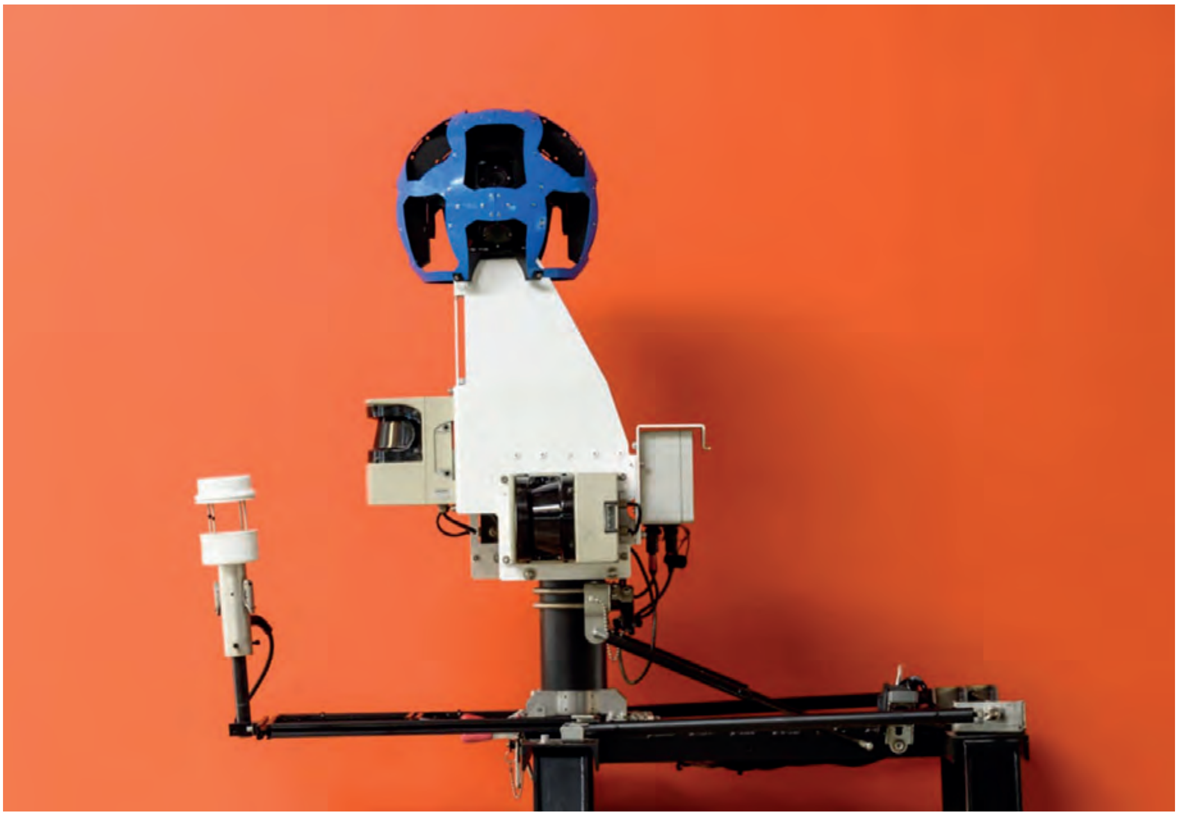
PM 10 concentration. The system draws rock-solid data from NOAA's global satellite forecast system and NASA's OSCAR comprehensive current database to generate visualisations of patterns and trends making it an additional resource for those involved in designs that are sentient to weather (Source: [10])

(e.g., ventilation, VOCs, particles). Data from social networks and geolocalised devices can be used to discover behavioural patterns of movement and permanence. Data from buildings' embedded sensors can be used to extract space use preferences. Emerging biometrics and wearable devices can be exploited in the design process. The use of mobile health sensors, sometimes termed mHealth (mobile health), is enhancing our ability to obtain direct measures of health. More simply, buildings keep generating data. Thermostats, water and energy usage meters, automated doors, light sensors etc. are being connected to the Internet.

Process and correlate data. If, until recently, data in buildings were used to treat one theme at a time (e.g., the energy demand), with the advent of the parametric digital design environment (e.g. Grasshopper a visual programming tool that interfaces with Rhino), it is possible to interlink several regenerative design themes and thus several data sets. For instance, it is possible to develop urban designs or buildings that cope with energy uses, resiliency, climate, biodiversity, health and emission mitigation goals at the same time.

Figure 14

Google streetcars are being equipped with air pollution sensors developed by Joe von Fischer, a scientist at Colorado State University. The data is sent to the Google Cloud for analysis and integration into a map showing the size and location of pollution. (credits: Google Sustainability)



The parametric modelling software continues to improve in accuracy, agility, and user-friendliness. However, if tools such as Grasshopper for rhino allow the integration of Data into design processes, this still comes with some challenges. The first is computational, as extensive data requires high computational performance.

Visualise. The representation of multiple themes and several data sets in infographics requires a certain familiarity with data management. The process of data analysis is quantitative, which often creates a barrier for users unfamiliar with these methods, particularly in design contexts. Therefore, a step in the process of working with big data is the communication and visualisation of data to facilitate its interpretation. In the field of building design, and in terms of spatial information, data visualisation plays a crucial role. The process of the display can be itself a part of the analysis when the way of presenting the data is so enlightening that it leads to the discovery of new meaningful knowledge not yet identified with solely quantitative methods.

Creative Spark. Finally, the translation of big data into a design requires depth of analysis, scientific ability and creativity. Further steps are needed to turn data into relevant design knowledge and productions; this takes a creative spark. The spark of the invention that can spill out onto the back of a napkin is still crucial, even when the complexity of Regenerative Design and the analytics of extensive data are involved. It should be argued that the real revolution of data in design is not in the generation of data; it will be in the ways that this data are used to inform regenerative solutions.

EXAMPLES OF OPEN DATA FOR REGENERATIVE DESIGN

The data revolution, which encompasses the open data movement, the rise of crowdsourcing, new ICTs for data collection, together with the emergence of artificial intelligence and the Internet of Things, are transforming society. New insights gleaned from real-time data mining can complement official statistics and survey data, adding depth and nuance to information on climate change, human behaviours and experiences. From remote sensing to observations crowd-sourced from people, technological advances are providing designers with much new information. In the cases of lack of data, a way to create design data and share it is crowd mapping.

Climate change Data. Monitoring the climate system is critical to achieve a better understanding of the changes that may occur due to global warming and to produce a built environment that responds to it. Given the context of combating climate change, current research has already been applying big data analytics, mainly in the aspects of energy efficiency, smart agriculture, smart urban planning, weather forecasing, natural disaster management, etc. NASA launched the Earth Observing System's flagship satellite, *'Terra',* in 1999. Terra has been collecting data about the Earth's changing climate, and these data are freely accessible (4).

Natural Disaster. There are historical data from natural disasters, such as, floods, storms, landslides, volcanic eruptions, tsunamis, earthquakes, etc., that are key in predicting, detecting and improving the management strategy for a variety of future natural disasters. These data can also be exploited to identifyexisting challenges and future directions for the design of cities and buildings that are resilient. Several Crowdsourcing projects provide useful information in these regards, and they make their big data accessible to the public.

Biodiversity Data. Today's biologists might be found tracking down answers to their questions about biodiversity in front of their computer screens, wading through vast amounts of digital data rather than physically exploring natural habitats. The Global Biodiversity Information Facility (GBIF) (5) share biodiversity data from museums and research institutions that operate genetic sequencing, and collect observations by amateur naturalists. The freely available datasets have more than 500 million marks and track the spread of invasive species, model the impact of climate change on biodiversity, identify areas in urgent need of protection, and monitor the effectiveness of conservation programs as well as the effect of the built environment on nature.

Agriculture Data. Agriculture is one of the most vulnerable domains to negative impacts of climate change. Its production heavily depends on natural resources, and agriculture itself is also one of the primary sources of Green House Gas (GHG) emissions. The relationship between agriculture and the built environment is key for future planning. The developments of big climate data and its analytics have prompted the widespread use of smart information management systems, precision agriculture, as well as intelligent automatedagriculture that have a huge potential for integration in design processes that, for instance, deal with nature-based solutions.

Real-time weather maps. Some of the publicly available data are collected by Earth Null School (6) (see Figure 12 and Figure 13). With this interactive map, it is possible to study how ventilation can be used for energy production purposes, or for strategising about the design of temperate cities. Radiation charts show the potential for active and passive strategies at the regional and the building scale. Finally, the breakdown of pollution types and concentration could drive both policies and designs to neutralise emissions.

Real-time air quality. The city of Santander in Spain has deployed 12,000 sensors to measure air quality, availability of parking spaces, and light levels to better manage the city and deliver services to citizens [7]. However, data is also available through Google. They are implementing a large number of applications and functions based on the analysis of direct or indirect big data, such as for monitoring the traffic and air pollution in real time high-resolution mas [8] (see Figure 14).

Diseases and water. HealthMap [9] is a freely available, automated electronic information system for monitoring, organising, and visualising reports of global disease outbreaks according to geography, time, and infectious disease agent. Big data is also useful in measuring environmental risks. Aqueduct [10] is an interactive water-risk mapping tool from the World Resources Institute that screens and calculates water risk based on parameters related to the water's quantity, quality and other changing regulatory issues in a particular area. Being free online, users can choose the factors on which they want to focus and zoom in at a specific location.

Material routes. Within building construction, data is at the heart of ensuring that waste is minimised and resources are used effectively. Data derived from smart sensors and connected technologies can play a crucial role in a design that reduces energy use, that accesses under-utilised assets, and where material flows are inefficient [11]. The use of Big Data for circular principles applied to design by designers is seen as key. We see similar trends in waste management, where big data analysis facilitates both route optimisation during waste collection and the incorporation of recycled materials into the economic circuit. Nevertheless, it is already the case that large quantities of feedback data have also enabled product designers to design more easily recyclable buildings. Big Data already produced by manufacturers is used to trace the location of valuable materials in the 'urban mine' for their reuse. However, what is designable and modifiable by designers is how design influences and is influenced by the flow of materials and their life cycle. Also, building components will be equipped to signal when they need maintenance, repair or replacement.

The recycling, the reuse, and the extension of the life cycle of materials allow the 'closing of the loop' and are central principles of the circular economy.

Health monitoring. The potential human health benefits of using cities and buildings designed with the support of data are only recently being investigated. Today, in the private medical sector, analysis of big data is commonplace [12] and can be seen in, among other things, consumer profiling and personalised services. Furthermore, predictive analysis is used for marketing, advertising and management in several types of commercial businesses. Similar techniques can be embraced to gain real-time awareness into people's well-being and to target aid interventions to vulnerable groups. A design that is carefully human centred needs to be supported by physiological data derived by monitoring. New types of real-time data about how people's vital parameters relate to use spaces, infrastructure and buildings, allow the creation of areas that support physiology and psychology.

Regenerative design is an approach that reinforces the state of health of the Ecosystem and people. This section has shown how the orchestration of data from various domains is central to regenative design. Big data unlock the ability of planners and designers to understand and act on their designs' impacts on issues such as climate change and human health, which have long been considered to be outside of the designer's expertise. What is not in question is the long-anticipated digital ability to holistically process data from several ecosystems, materials and human subjects within digital models.

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BIG DATA, SOCIAL NETWORKS AND WELL-BEING

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Social Networks aimed at understanding well-being could sustain the shift in paradigm from Sustainable to Regenerative Design. Well-being, i.e. '*the state of being comfortable, healthy, or happy*', is a concept related to happiness, positive experiences and pleasure with implications on physical, mental, social and environmental aspects [1]. In the built environment, recent works have linked indoor comfort, as well as long-term mental health and illnesses, to Indoor Environmental Quality (IEQ) [2]. Further studies focusing on outdoor spaces were conducted on the relationship between landscape and well-being [3], proving how urban landscapes affect the physical, mental and social well-being and health of citizens. Recent studies have also shown a positive impact of social ties on health [4] and the value of adopting a socio-ecological approach to co-benefit individuals and the ecosystem, thus calling for integrated governance of social-ecological systems [5]. However, there are only a few projects that focus on the integrated governance of a social-ecological system with ubiquitous technologies, and these projects are highly focused on human-centric design rather than on an eco-centric perspective [6]. Ubiquitous technologies, also defined as ambient intelligence [7], refer to sensitive environments where computing is available everywhere at any time and may allow a more regenerative design by taking into account all the components of an ecosystem and their interactions.

FROM HUMAN TO ECO-CENTRIC PERSPECTIVES

The sustainable development definition, officially introduced by the Brundtland Report [8], reflects the anthropocentric view in which rights and duties are only attributed to humans. This view has been criticised since the 1970s when the sustainability debate emerged. According to the Deep Ecology ethics [9] - *the development would not be right if the ecosystem is significantly affected by it* - rights and duties must also be prescribed to smarter animals, sentient beings, living beings and *beings in existence*. In 1984, *'A Cyborg Manifesto'* introduced the Posthuman theory, rethinking the human experience and establishing the idea of a collective nature [10].

It is argued that humans cannot control the ecosystem, but they are a part of it together with non-human entities, living and non-living objects. This new paradigm is embodied in the *Sustainable-Restorative-Regenerative* shift [11]. *Sustainable* represents an old anthropocentric viewpoint that is focused on limiting negative environmental impacts. *Restorative* design highlights an approach to restore eco-, social and economic systems to a healthy state, and the new paradigm represented by the *Regenerative* approach, which aims to enable ecological, social and health co-benefits.

In the next section, three pilot projects explore indoor and outdoor human well-being, comfort and health in parallel to the above mentioned ecological, social and health co-benefits: 1) *ComfortSense* adopted a Mobile Crowd Sensing approach (MCS) for Adaptive Thermal Comfort, 2) *HOME (Human Observations Meta-Environment)* explored the direct interactions between occupants and the building to improve indoor comfort and reduce the energy consumption of Heating, Ventilating and Air Conditioning (HVAC) systems, while 3) *First Life* tested a Neighbourhood Social Network to foster citizens' interactions in identifying specific places within the city with positive or negative implications for well-being and health.

MOBILE CROWD SENSING APPROACH (MCS)

A recent project, *ComfortSense* [12], was aimed at improving users' comfort while reducing energy consumption by exploiting a machine-learning algorithm to correlate Objective variables (Temperature, Humidity and CO_2 concentration) with Subjective feedback from users. The personal feedback was gathered through a mobile app, thanks to a Mobile Crowd Sensing approach [13], to stimulate a behavioural change process in occupants to adapt the building in response to the users' perception. Figure 15 shows the IT infrastructure designed to interact with people (data visualisation) and with the building (optimisation) to improve the whole system (decision support) by reducing the energy consumption and improving occupants' indoor thermal and visual comfort.

ComfortSense was based on an Adaptive Comfort approach [14]. The Adaptive Comfort models are based on the idea that people, by interacting with the building or the environment, can control the environmental conditions, such as the indoor temperature or the relative humidity. In particular, ComfortSense linked users' feedback to Indoor Environmental Quality (IEQ) monitoring in real time by exploiting the smartness of collective intelligence, i.e. a crowd/group may often make better decisions than any single member of the group [15].

A regenerative state can be activated by considering that occupants tend to forgive more, e.g. they may accept higher indoor temperature during the summer if they have more control over the building itself [16]. Taking into account the basic principle of adaptive thermal comfort, ComfortSense showed how indoor comfort could be improved to achieve health co-benefits for humans (reduction in headache, nausea and dizziness) and for the environment (reduction in consumption [12]).

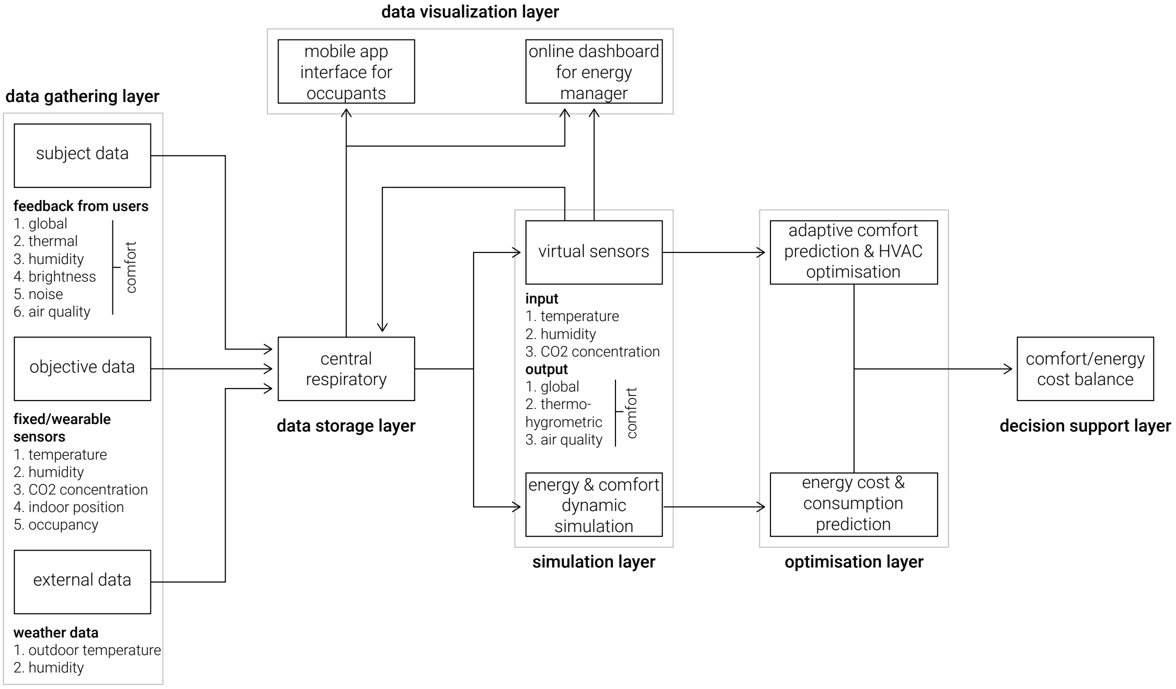


Figure 15

Information flow of the ComfortSense project. The six layers allow interactions among occupants, the building and the energy management. The data gathering layer collects data from sensors and occupants which are first stored into the data storage layer, then used to train the predictive algorithms (simulation and optimisation) and finally organised for users (data visualisation) and energy management (decision support).

HOME (Human Observations Meta-Environment) [17] focused on the use of Social Networks for improving well-being and thermal comfort by exploring the process of *environment-emotions-health* [18], i.e. how the surrounding environment affects, positively or negatively, peoples' emotions and how the latter may affect human health. For this purpose, HOME created an interactive environment where occupants act together with the building via social media feedback. Users control the indoor temperature by sending messages, such as 'up' or 'down', or by writing comments that are captured by the software Human Ecosystem [19]. Signals were correlated to indoor temperature, humidity, occupancy density and users' movements tracked with videos processed by the OpenCV library to transform video information into data. Causes of discomfort and unhealthy states were analysed by looking at the emotions manifested in comments. Figure 16, 17 and 18 show three screenshots of the possible visualisations used to analyse users' feedback and sentiments.

Figure 16

Screenshot from the Human Ecosystem dashboard analysing posts from social networks. The comfort/energy distribution (bottom-left) shows qualitative classifications of comfort/energy. Each post/tweet has been classified by two parameters, comfort and energy, by assigning two values to words within the scraped sentence in order to explore the phase space of the Circumplex model of emotions. The energy parameter defines an active or passive action, while comfort describes a positive or negative concept.

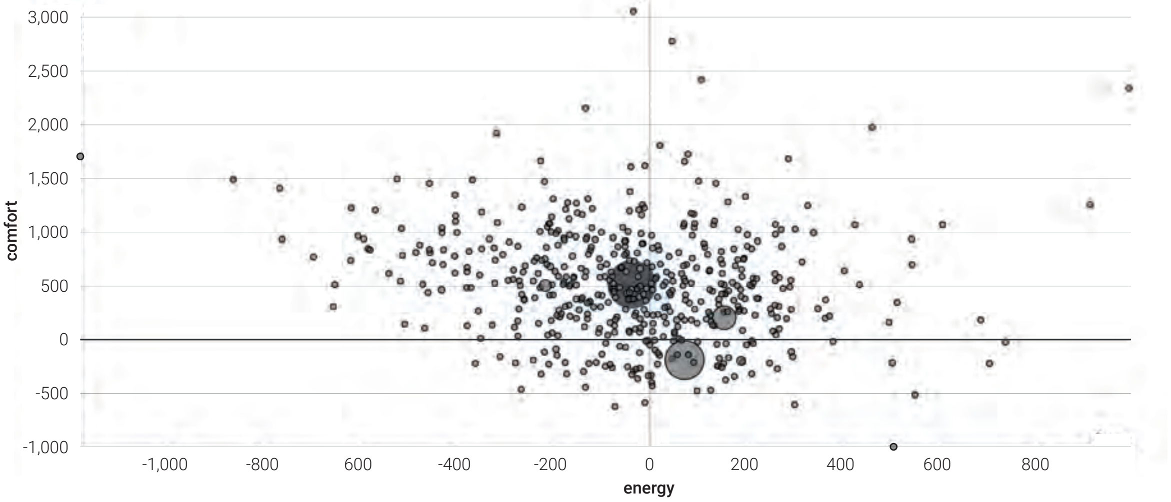


Figure 17

Screenshot from the Human Ecosystem dashboard analysing posts from social networks. The wordcloud highlights the most frequent words appearing in scraped posts and tweets.

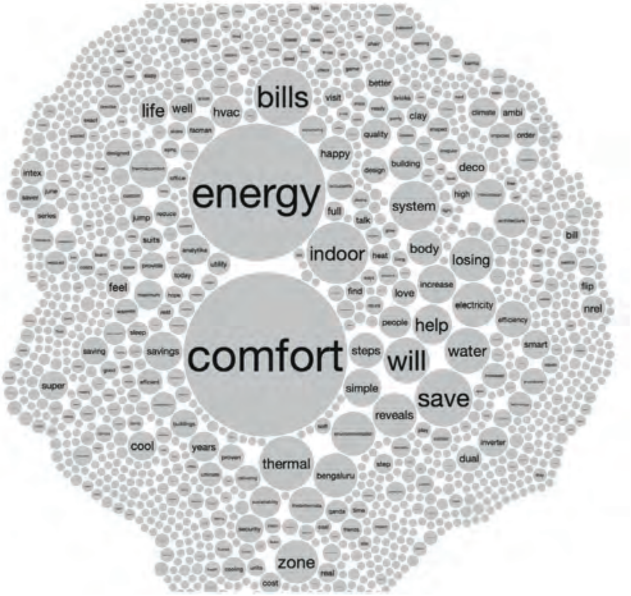
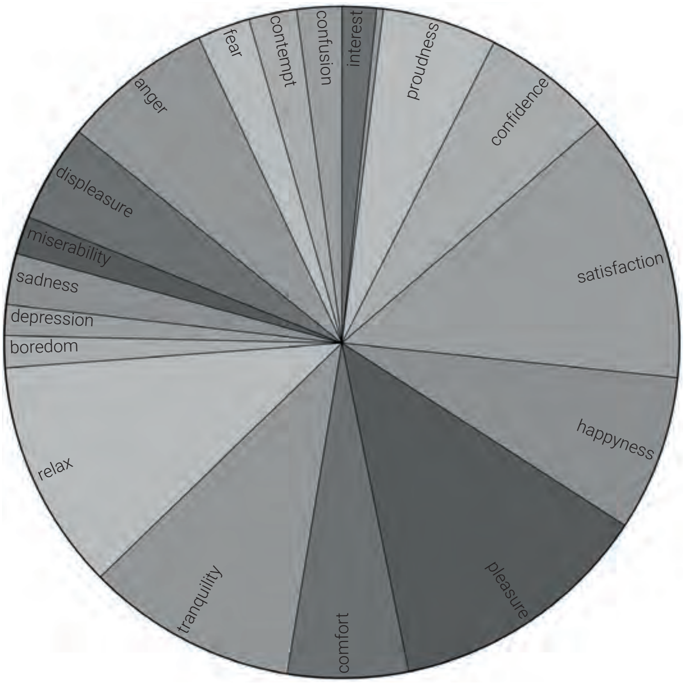


Figure 18

Screenshot from the Human Ecosystem dashboard analysing posts from social networks. The piechart summarizes the most frequent sentiments of the scraped posts/tweets. Emotions are defined with precise keywords belonging to the Circumplex model of emotions such as Happiness, Tranquillity,Displeasure and so on.



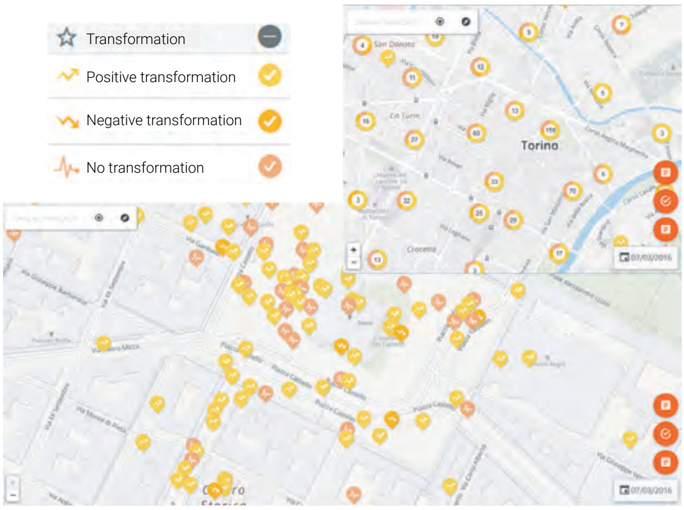


Figure 19
Screenshot from the First Life web platform. The map shows the current transformation occurring in a place within the City of Turin, as perceived by the citizens engaged within the project. This map is only one of the available visualisations of the First Life platform [20].

FirstLife [20] is a web platform for Computer Supported Cooperation aimed at fostering co-production of urban landscape knowledge. It provides a virtual place, a *Neighborhood Social Network*, where citizens can interact and participate in city life. FirstLife can be exploited as a pure Digital Urban Acupuncture (DUA) approach to explore the daily microhistory of citizens. The DUA approach is an innovative approach, introduced by Iaconesi et al. [19], useful in identifying the *Pressure Points* between citizens and the urban landscape, or between occupants and a building.

The Pressure Points are the contact points which cause conflicts among the different actors, i.e. citizens/occupants and the buildings/urban landscape. Indeed, concerning personal indoor comfort and according to the main principle of Adaptive Comfort - *if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort* [14] - such points represent the most interesting part of the occurring interactions between actors and the environment. Once the pressure points are identified, new punctual strategies may be adopted to improve actors' comfort, well-being and health.

For instance, decision makers could focus on unhealthy places and plan to redesign them in a regenerative way by taking into account natural and artificial places appreciated by the citizens, such as small court gardens or fountains, which have positive implications on community health [3] but are typically underestimated from the decision-makers' point of view. Thus, thanks to this approach, a more Regenerative city, able to co-benefit humans and the environment, can be designed. Figure 19 shows an example of visualisation from the First Life platform, where positive and negative transformations as declared by the citizens, are highlighted and geo-localised to support the decision-making process of urban planners and policymakers.

To sum up, the substantial implications of the surrounding environment on human indoor and outdoor comfort, well-being and health have been widely investigated in the past decades, but previous research has mainly focused on a human-centric perspective. The presented approaches and the use of ubiquitous technologies could help in understanding dynamic relationships between humans and the environment, which would, in turn, allow better applications of Regenerative Design for the built environment and the urban landscape. More in-depth investigations into the adoption of integrated governance, are needed to consider the main dynamic interactions in real-time, i.e. the Pressure Points as defined by the Digital Urban Acupuncture approach.

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BIG DATA IN REGENERATIVE URBAN DESIGN

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While Big Data is now routinely used in some industries, its value has yet to be exploited in regenerative planning matters. While various cities are adopting smart and innovative solutions to strengthen the sustainability and resilience of urban fabric [5], they often lack a more holistic approach. In many cases, they are based on sectoral initiatives, for example, isolated transport solutions such as smart intersections, instead of introducing integrated frameworks leading to more sustainable mobility patterns. Moreover, a strongly technocratic narrative still dominates, which is evidenced by initiatives often being limited to enhancing the efficiency of the distribution systems and developing the market for smart appliances [6] instead of providing a change in response to the needs of the users.

Knowledge of Big Data is still spread and unstructured, and therefore, its usability in supporting both planning processes and decisions is not yet fully recognised. So far, many Big-Data-based urban solutions have been tested [11]. However, access to numerous databases that could be used in supportive tools for urban development simulations is still limited, so their use in shaping sustainable, regenerative solutions is not fully embraced.

To provide a model to assess numerous Big-Data-based urban projects to facilitate novel solutions, both the process and criteria for case study selection were designed based on previous research [3]. The objective is to identify tools using large datasets, which – by combining existing solutions – can help to achieve a more holistic approach and facilitate the regenerative design.

The main criteria for case study selection were the presence of key elements defining the regenerative approach. However, additional aspects such as (a) the scale of implementation, (b) planning phases and (c) project scope were considered to analyse the diversity of existing solutions. For each case, data sources were studied and classified using the Thakuriah (et al.) [14] typology (sensor systems, user-generated content, administrative, the private sector and hybrid data). It was proven that any type of such data could support regenerative planning and design processes.

Selected case studies are presented in the matrix (Figure 20), where examples corresponding with the aims of sustainable development are presented in rows, while the type of data used in analysed projects is presented in columns. An additional (last) column indicates the scale of implementation. This matrix shows the diverse possibilities of using Big Data sources.

BIG-DATA-BASED SOLUTIONS SUPPORTING A REGENERATIVE DESIGN APPROACH

As numerous research points out [13, 5], there are opportunities to enhance regenerative planning by using assessment tools combining clear cases of regenerative implementation with data mining analysis or surveys. The use of user-generated content provides an opportunity for access to opinions of the city dwellers. Therefore, tools based on such data and methods can often be considered an essential source of information for introducing supportive urban solutions. In particular, they are useful for:

- Shaping policies and strategies aimed at improving safety or health conditions – e.g. Street Score [17] where the users' perception of urban space is measured based on photos posted online,
- Strengthening planning participation by introducing tools for collecting opinions posted online, e.g. project of M-Participation by Erito [18],
- Providing well-organised, efficient transportation systems, e.g. MobiliCities [19],
- Evaluating city connectivity and accessibility to public services, e.g. analysis of the Dakar Metropolitan Area by Fetzer and Sy [20],
- Recognising environmental sensitivity by using sensor systems to measure changes of local microclimate when implementing new projects for public spaces, e.g. studies by Huang et al. [21],
- Supporting decision-making processes to build social equity in the living space within urbanised areas, e.g. Data-Pop [22] project,
- Measuring the digital economy, e.g. project tested in Latin America [23] by linking business (private sector) data with statistical information,
- Introducing tools for improving the energy efficiency of the built environment, e.g. Google Project SunRoof [24].

Figure 20

Research summary - case studies, data sources and the scale of implementation. Source: Authors' elaboration [3]. The figure presents a matrix for sectoral use of Big Data sources. Based on selected case studies, it shows in which field such data can be supportive and on what scale it can be considered for achieving reliable results. The figure proves the lack of a holistic approach, which is necessary to help to implement regenerative oriented solutions.

selected projects	data sources							scale of implementation
	sensor systems	**user-generated content**		**administrative (governmental data)**		**private sector data**	**hybrid data (linked and synthetic)**	
		social media	gps	personal microdata	spatial information			
1. social & cultural active, inclusive & safe predictive policing preventing crime with data and analytics		●	●	●		●	●	neighborhood/city
2. governance well run m-participation the emergence of participatory planning applications		●		●			●	neighborhood/city
3. transportation & connectivity well connected mobilicities			●		●			city/region
4. services well served the dakar diamniadio toll highway & increase of human mobility			●		●			neighborhood/city
5. environment environmentally sensitive microclimate, outdoor thermal comfort the human experiment	●				●			neighborhood
6. equity fair for everyone data-pop big data and people			●			●	●	neighborhood
7. economy thriving digital economy in latin america and the caribbean				●		●		city
8. housing & built environment well designed & built solar potential of your community, U.S. project by google	●					●		neighborhood

The list above shows only chosen cases. The present study together with the author's previous research [3] confirms the findings of Zanella [1], stressing that there are already existing systems based on Big Data capable of capturing and monitoring human-ecosystem relations in urban space such as the occupancy-based model for efficient reduction of HVAC energy, created by Erickson, Carreira-Perpiñán & Cerpa [23]. At the same time, the range of the analysed project is, in the majority of cases, sectoral; i.e. connected with participation, transport or energy efficiency. No holistic projects using Big-Data-based tools to integrate different systems of the city were found among the analysed cases. As Big Data describes the phenomenon continuously rather than at a given point in time, it can be considered an appropriate tool to assess a circular approach (based on reuse of space and monitoring urban flows), instead of states. The analysed case studies focus not only on the mitigation of negative phenomena but also on the creation of positive balance - a feature of the regenerative approach.

CONCLUSIONS ON THE INTEGRATION OF BIG DATA WITHIN THE REGENERATIVE DESIGN

Introducing examples of projects where Big Data is used as a supportive tool shows that sustainable development processes can be enhanced in all phases: *planning* (recognising needs), *designing* (programming solutions) and *evaluation* (improving the design). However, only when integrating data sources and different sectoral Big-Data-based urban interventions as described in the collection of the case studies can planners introduce a holistic approach that allows the support of regenerative development of human settlements. At the same time, the research shows that, unfortunately, not many integrated urban solutions have yet been implemented or tested. There is a strong need to change the sectoral approach and adopt more holistic solutions that utilise Big Data.

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MACHINE-LEARNED REGENERATIVE DESIGN

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One of the most important developments in the area of Architecture, Engineering, and Construction (AEC) will be the way designers relate to climate change and the notion of climate adaptation as a primary response to the environmental pressures from climate change. Before we move into solutions, there is a need to understand and critically reflect on what adaptation, within the realm of design, really means and how it is apparent in nature, which is a constant inspiration for environmental design innovation.

A critical reflection always begins with an attempt to clarify and define important aspects of a problem. There are currently three major misconceptions in the AEC industry, nested within three important processes of design: Parametric Design Optimisation, Ecological Design and Evolution, Climate Adaptation.

PARAMETRIC DESIGN OPTIMISATION, DESIGNING WITH PARTIAL INFORMATION AS THE NORM

Parametric Design (PD) is defined as *'a process based on algorithmic thinking that enables the expression of parameters and rules that, together, define, encode and clarify the relationships between design intent and design response'* [1]. The word parameter is at the core of parametric design, but the 'relationship between design intent and design response' is as crucial. It is this relationship that parametric design is supposed to uncover to inform the design and allow it to be optimised iteratively and in a quantitative manner.

Unfortunately, in practice, this relationship is rarely adequately explored. The misconception here is that we think this partial understanding is enough to properly inform the design process in a 'better less than nothing' approach. Practitioners claim to have 'parametrically optimised' their designs even if a handful of scenarios, a fraction of the possible design space, are assessed. The industry is being short-sighted here in a very literal sense; while it can 'see' the most minute of design spaces, it is unable to explore any significantly sized design space, at least under most performance-based evaluations.

Bellman's notion of the curse of dimensionality [3], the exponential increase of design alternatives in high-dimensional spaces, is not something unique to AEC but has had a tremendous effect on the quantity and quality of our design spaces and processes. Even a simple box model with minimal computational requirements, often used as a proxy in the AEC, suffers from this curse (Figure 21). The exponential increase of design alternatives, computational time, and resources required to conduct comprehensive parametric optimisation studies is one side of the problem. The fact that this leads us to design spaces with incredibly sparse parameters is another much more important and underestimated problem. It seems that the curse of dimensionality limits not just our design spaces, but our creativity and imagination as well.

ECOLOGICAL DESIGN AND EVOLUTION, NOT AS CLOSE AS WE THOUGHT

So how are we to overcome all this? Various Ecological Design approaches have been widely used in AEC for many years in trying to tackle this very problem [4]. Perhaps the most popular has been Evolutionary Optimisation (EO), and specifically Genetic Algorithms (GA), which are often employed to find optimal solutions to difficult problems. The core idea is to start with a few simple rules (parameters) and allow for complex systems or designs to emerge. To reduce the dimensionality of the problem and the number of alternatives needed to be assessed, the optimisation process then focuses, and indeed filters, the best performing alternatives instead of exploring the design space itself.

the curse of dimensionality

	design alternatives	time
playing with façade orientation (8) * wwr (7) * sill height (2) * glz specs (3) * wall specs (3) * shdg lenght (3) * shdg angle (3) * shdg orientation (2)	6048	50 hours
climate * location (6)	36288	300 hours
indoors * hvac (4)	145142	1200 hours or 50 days
massing * shapes (4)	580608	4000 hours or 200 days

Figure 21

The basic mathematics of parametric design optimisation. The explosion of design alternatives, even under simple parameter combinations, is a significant bottleneck for conducting truly parametric optimisation studies.

However, what if nature did not evolve in this way? What if the beginning of life was much more complex and beautiful than we thought? What if there were more designs then than there are now? I was fortunate to find an unexpected inspiration on this topic in *'Wonderful Life: The Burgess Shale and the Nature of History'*, an incredible view into the [hi]story of life by the great evolutionary biologist Stephen Jay Gould [5]. Gould completely deconstructs and then reassembles the notion of evolution, changing everything we once thought we know about it, including the ecological design principles we habitually apply in our generative design processes.

It turns out, Gould tells us, that at the beginning of life, deep in the Cambrian sea almost 500 million years ago, there was more design diversity (more unique design archetypes) than exists today! Perhaps not surprisingly, nature is a better parametric design optimiser than us. It is crucial to point out that this indicates that the richness and diversity of nature do does not seem to be the result of 'millions of years of evolution and natural selection', a popular catchall phrase. Instead, it was the condition of open exploration and experimentation from the start that was crucial for the development of the wonderful story of life as we know it.

CLIMATE ADAPTATION, SOLUTIONS BEGIN WITH NEW DEFINITIONS

This brings us to our final misconception, *adaptation*. Inspired by Nature once again, we have selected 'adaptation' and 'resilience' as the central paradigms of ecological strategies that are currently being developed and implemented to combat climate change, perhaps the single most important issue of our generation. The notions of 'adaptation' and 'resilience' are both related to the flexibility of designs, policies, and strategies, which allow our urban environments to return to their previous states after sudden shocks, climatic or otherwise.

At first, glance, designing environments that can withstand shocks seems to be a logical choice on our part, as, after all, we do like this kind of stability. However, Nature once again does not operate in such a manner. Nature has never been simply flexible but has always had the capacity of differentiation and radical transformation under adversity and contingency. In this sense, Nature is much closer to what neuroscientists would call *plasticity*; that is, the explosive potential for differentiation and functional change [6]. If we hope to indeed reverse the course of environmental degradation with strategies that will make for truly resilient cities, we need to turn to plasticity as our core principle of design.

This would mean that our designs need to not only be able to adapt and resist climatic pressures but be able to differentiate themselves under varied environmental conditions. We need to learn to design for all *contingencies at once* without sacrificing performance. This means that designs, and by association our design processes, can no longer be passively subjected to predefined heuristics but need to become active subjects of creative transformations. The potential for ‘resistance,’ ‘negation,’ and ultimately ‘explosion’ that plasticity offers will bring new transformative possibilities for the future of design [7].

BRINGING IT ALL TOGETHER; FROM DATA TO INTELLIGENCE-DRIVEN DESIGN

The big question, of course, is how to design for all contingencies at once without sacrificing performance. How can we escape our preconceptions, disrupt our design thinking, practices, and workflows? How can we learn to be curious and playful? Finally, how can we design buildings and cities that can not only survive but thrive under many conditions at once? My claim is that Machine Learning (ML) can be the framework under which we can finally integrate the above ideas in our design processes. Thought out and implemented thoughtfully, avoiding the hype and all the noise, ML can change the nature of the relationship between learning and design, allowing us to do the parametric design on generative scales!

Implementing ML requires us to change various aspects of design and optimisation processes. We first need to develop AI-capable design environments that can handle and export large volumes of different types of data (tabular, image, semantic, etc.). We need to connect these environments to the many different ML frameworks in an efficient and transparent way. Finally, we need to follow the AI industry’s example in developing this new constellation of design software in an open-source and accessible manner. Only in this way can we hope for the dissemination of knowledge and ML-infused workflows in the AEC industry at the pace at which we need them.

All this should give us the chance to start our designs from the point of diversity, just as life did all those millions of years ago. It should allow us to finally shift our focus from the almost obsessive, goal-driven optimisation to the more playful design exploration, a process of learning from the design space itself. If we are lucky, one day this might even give us the chance to be surprised by our designs, to broaden our thinking and design practices to include the notions of plasticity and differentiation, leading to truly resilient designs that are gravely needed under the pressure of climate change. After all, isn't the goal to have a positive impact on our world?

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NEW METRICS FOR DIGITAL REGENERATIVE DESIGN

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The recent explosion of digital tools for environmental analysis has made it easier than ever to 'do less bad'. Measuring the damage we do today and reducing that of tomorrow is not yet trivial, but there are countless software packages and metrics available to help. Regenerative design, however, holds designers to a higher standard, and actively improving human and environmental health requires more than an arsenal of metrics. Improving health requires a vision greater than any single number, and oversimplification poses a danger of treating the newly available tools as implements of technocracy. Few architects enter the field of design to be technocrats; most are motivated by creativity. The design process can be a turbulent sea to navigate, and a project's destination is ultimately determined through discussion. Digital tools play a key role in describing regenerative strategies within these design discussions.

The last several decades have seen a gradual transformation in the digital tools themselves, from tools which were designed specifically for evaluating HVAC systems towards tools intended to assess the performance of an entire building. The family of plugins in Ladybug Tools builds further upon this development and acts as a node between the realms of building science, thermal comfort analysis, and architectural design [1]. Architects can now retrieve a great variety of daylighting and thermal comfort metrics at the level of spatial precision necessary for making design decisions. This astounding degree of analytical flexibility has resulted in a subsequent Cambrian explosion in forms of digital analysis. Designers can build a systematic framework specific to the questions of each project.

The result is that architects now have access to rich bodies of information composed of multiple metrics when making design decisions. This opens possibilities for regenerative strategies, but it also makes it necessary to choose which metrics are most important. It will always be easier to optimise isolated measures as an effort to 'do less bad' than to map the constellation of metrics which prove a proposal is actively contributing to human or environmental health.

David Benjamin's collection of essays – '*Embodied Energy and Design, Making Architecture Between Metrics and Narratives*' - addresses the difficulties of relying on any single measure [2]. Net Zero excludes embodied energy. Embodied energy does not necessarily imply reduced emissions. Reduced emissions are but a tiny part of human well-being. It seems the path forward requires a vision for health that triangulates many available metrics, weaving them into a coherent narrative.

QUANTIFY THE IMPACT OF DECISIONS

Such a muddy terrain greatly benefits nimble architects, who can quantify the impact of their decisions. One obstacle is that traditional architectural representation requires training and experience to read. The lines locating walls on a plan drawing might be explicit, but the reason for their configuration is often left implicit. Where is the sun shining? When? How does it interact with the breeze? Would more thermally massive walls make the design better or worse? The challenge for designers is to assess the cumulative impact of many effects and ultimately document the value that their decisions implicitly create.

This is not a form of analysis that can be easily outsourced to engineers because it is intertwined with the creative process. Fortunately, it is possible to greatly smooth collaboration with engineers because these tools offer architects the capacity to communicate more precisely than before. Take deciding on a window-to-wall ratio as an example. Prior to the advent of these tools, an architect might have had to rely on a single value for the window-to-wall ratio of an entire building. Now, architects can arrive at an engineering meeting with printed elevation drawings of every facade specifying levels of solar radiation for all hours of the year per square meter. This is a dramatically different starting point for discussion that creates possibilities for more holistic decision-making.

Architects have been the party responsible for crafting these arguments on behalf of holistic quality for millennia. Vitruvius divided this responsibility by distilling architectural quality down to firmitatis, utilitatis, and venustas (stability, utility, and beauty). Today, the assessment of design quality is fractured even more and scattered among countless specialists. However, architects are still the party responsible for assembling these fragments into holistic regenerative strategies. For example, an external canopy might play a regenerative role by increasing outdoor comfort, blocking solar radiation, and collecting rainwater. Quantifying these benefits makes it possible to speak the same language as retail consultants who want to see increased foot-traffic, engineers who need to size HVAC, or municipalities concerned about water infrastructure. Digital tools offer the power to express design options in precise, data-oriented, and contemporary terms.

DATA VISUALIZATION

Visualising simulation results not only makes the information available to the design process, but it also changes the way that data is interpreted. The pairings of analysis in Figure 22 and Figure 23 illustrate this idea. Figure 22 illustrates the difference between evaluating an entire room abstractly (left) and focusing on the needs of an artist who intends to paint in that room (right). This represents a shift in the unit of analysis from the room to the occupant. Metrics like Spatial Daylight Autonomy for LEED or Daylight Factor / Uniformity Ratio for BREEAM only reward homogenous lighting over an entire room or floor. This is useful information, but it only approximates the needs of any specific activity. It also rules out the possibility of the shadow being desirable. Figure 23 offers an example of how visual interpretation of data might steer the design changes. The abstract representation (left) shows a balcony that receives a significant amount of direct sunlight but placing human figures on the balcony (right) makes it clear that only one person can sunbathe at a time. This is a qualitative conclusion based on the same quantitative output but may lead to a different design outcome. Figure 24 shows four complementary representations of sunlight, which offers a glimpse into the assumptions built into different types of daylighting analysis.

These tools may pave the way for introducing joy into the repertoire of regenerative architectural qualities. The notion of thermal joy based on contrast has existed for decades. Lisa Heschong's meditation on solar heating, *Thermal Delight in Architecture,* explores many forms of thermal joy in design, particularly those related to the sun [3].

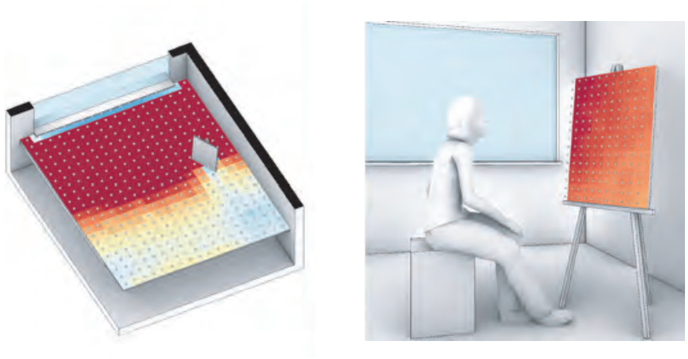


Figure 22
This figure illustrates how curating simulation data can impact its interpretation. These two images show the difference between evaluating lux levels of an entire room abstractly (left) versus focusing on the needs of an artist who intends to paint in that room (right).

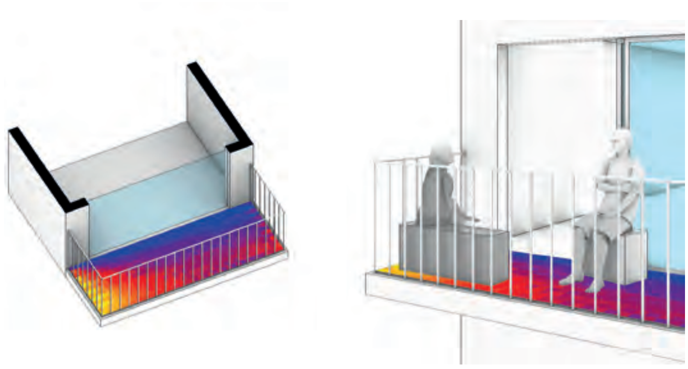
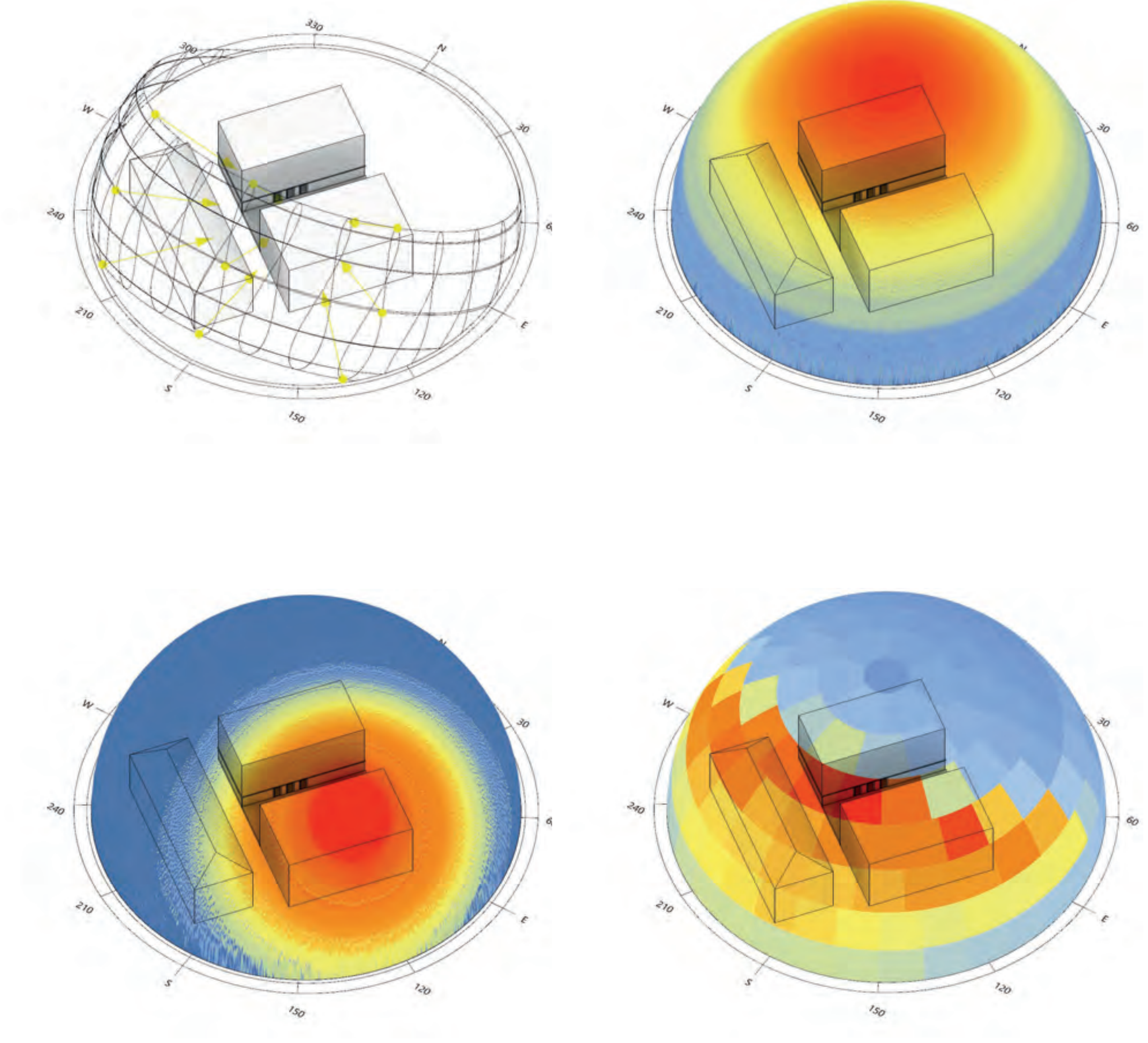


Figure 23
This figure illustrates how placing human figures among simulation data can offer context. The abstract representation of hours of direct sun (left) benefits from scale human figures (right) because they show that only one person can sunbathe at a time.

Salmaan Craig, a pioneer in architectural heat-exchanger design, paints a more recent portrait of thermal pleasure based on the contrast in his essay entitled ‘Beyond Thermal Monotony’ [4]. He notes how remarkably sensitive human skin can be and describes how sharp thermal contrast shapes the lives of our evolutionary cousins, the Macaque Monkey, who live in the hot springs and frozen mountain-scapes of Nagano, Japan. The ability of these digital tools to infuse the design process with data on temperature gradients or maps of solar radiation may result in more than the sum of the individual parts.

Figure 24

Four different types of daylighting analysis. Clockwise from top left: 1) a geometric tracing of the annual sun path; 2) a CIE diffuse sky used for Daylight Factor, which ignores the direction from which the sun comes; 3) a climate-based sky that represents a snapshot of the sky at 9:00am on March 20th; 4) a Tregenza sky dome which represents the cumulative intensity of radiation over an entire year.



INTEGRATE THE DEVELOPMENT OF TOOLS

Digital tools are also a point of contact between the ideas that regenerative design embodies and built projects. In this regard, it is important for designers to integrate the development of these tools and to demand that they reflect expected conditions. For example, it is only recently that adaptive comfort research emphasised that high air speeds can be beneficial in warm environments [5], while it seems obvious that a breeze is pleasant in the summertime. This gap could have serious implications for the tropics and the Majority World. In terms of ensuring access to these tools, it is also important to insist on tools which are adaptable, affordable, and well-documented [1]. The latter is especially important because these tools are new, and it is easy for designers to drift astray inadvertently. It should be common knowledge, for example, that Daylight Factor was developed for the cloudy weather of the United Kingdom, and that it is a poor measure in areas with strong direct sun, like the tropics. The quality of results from introducing these tools to practising architects will be determined by the ability of practitioners to stay abreast of underlying assumptions and new developments.

Quantifying regenerative design poses challenges that simply ‘doing less bad’ does not. However, the digital tools available offer a constellation of metrics and measures for bringing a coherent narrative to complex contexts. This opens creative possibilities and makes it possible for architects to cross-reference many forms of analysis. As architects gain access to this information, they will acquire an added power to argue for the value that design implicitly creates, but they also inherit a responsibility to be critical of the tools at their disposal.

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RISKS AND NEEDS OF DIGITAL REGENERATIVE DESIGN

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Regenerative design processes are those in which design aims and targets go beyond currently established sustainable and environmentally friendly paradigms. Regenerative design solutions should positively contribute to the ecosystems in which they are inserted, thereby regenerating the environmental qualities of site and context to its original condition and beyond [1-4], an ambition that requires a substantial amount of evidence from concept generation to concept validation. Thus, designers nowadays make extensive use of digital tools not only to explore design possibilities but also to generate evidence-based design solutions, especially when required to gauge sustainable aspects and energy targets [5-8]. However, in practice, little is discussed in terms of risks and needs associated with the use of these tools. There are a set of risks and needs associated with integrating digital tools into the conceptual stages of regenerative design processes.

It is thus key to reflect about when and why digital tools are necessary throughout the design process considering the types of solutions practitioners tend to induce, the level of expertise needed for their operation and the range of uncertainties associated with the evidence they are supposed to produce. The discussion arises from an empirical study based on observing four groups of highly qualified designers and consultants working in collaboration on a conceptual design competition applying regenerative design principles and using parametric design tools to regenerate the neighbourhood of La Luz located in Malaga, Spain (Figure 25 and 26).

The design competition was part of the '*Regenerative design and digital practice*' Autumn training school from the EU COST Action Restore, which took place in the school of Architecture of the University of Malaga between the 15th and 19th October 2018.

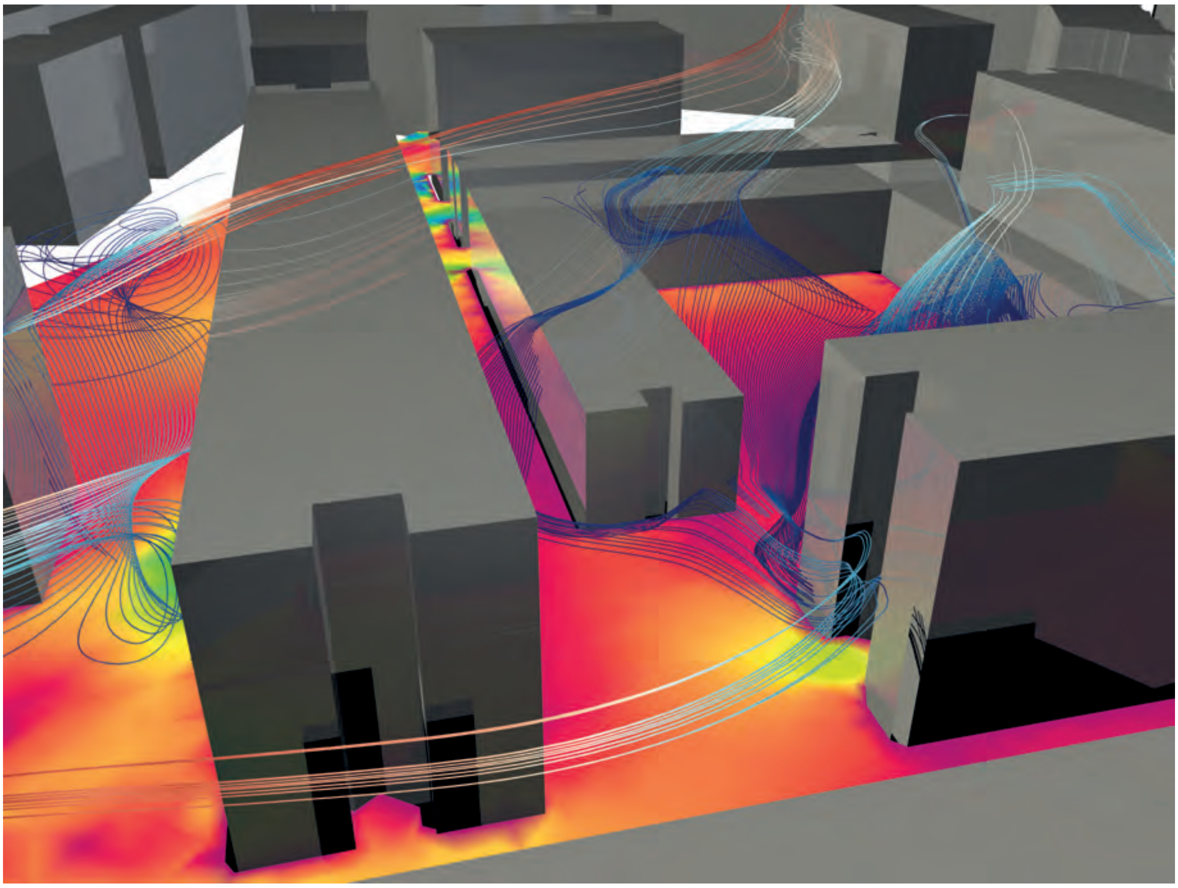
Figure 25

The experiment was conducted using as reference the Barrio of La Luz in Malaga, built around 1960, the teams had to propose retrofit solutions to achieve regenerative targets.

Observations comprised: (i) attending sessions in which each participant presented their current work, (ii) recording design development sessions using 360° portable digital cameras and dictaphones, and (iii) video recording and observing training school tutorial sessions related to regenerative design, integrated design, human well-being, parametric design and life cycle assessment, attended by one representative member of each group. Preliminary results are extracted from the discussions that took place in tutorial sessions of regenerative and integrated design. Some of the discussion highlights are listed below and are followed by a set of provoking questions to stimulate further thinking.

CAUSALITY VERSUS PRODUCING EVIDENCE

The first discussion highlight was the causality dilemma of using evidence to make decisions versus producing evidence from decisions. Concept developers reported waiting for data analysts to generate evidence so they could propose/make decisions, and at the same time, data analysts reported waiting for concept developers to generate ideas so they could test them. Particular cases in which this occurred involved concepts that needed evidence and/or testing of wind patterns, energy use and water collection and storage.



Discussions around this dilemma constantly revolved around the type of evidence to be produced and the best ways to display such evidence, pushing analysts also to propose changes and develop concepts further. This observation yields two critical questions for the design process: What kind of evidence do concept developers need to be able to make decisions? How can data analysts produce tests that are less focused on diagnosing problems and are inspirational to expand the search in the design solution space?

Narrowing the search in the design solution space while attempting to solve in depth a particular environmental design problem or while proposing a particular regenerative design solution led to another interesting question: *Is it better to go for a punctual intervention or to adopt a systemic approach?* An example of a more systemic approach was rethinking the mobility system to increase the area for green spaces and attempt to regenerate the water ecosystem. The danger of a systemic approach is the level of cooperation it requires different stakeholders at multiple scales.

Figure 26
The involved teams used a full set of algorithms in Grasshopper and ladybug Tools. Here is an example of one of the simulations operated by the teams where Computational Fluid Dynamics (CFD) was used to account for the Urban Heat Island modelling.

For instance, one cannot expect a reduction in the use of cars to increase areas dedicated to green spaces without a reliable and frequent public transport network. On the other extreme, it was clear that a punctual intervention, almost in the form of a 'gadget', was used as a powerful reinforcement of a design statement, for instance when a major piece of built infrastructure was proposed to induce specific wind patterns and provide solar shading.

As opting for punctual interventions can easily lead to a spiral set of 'side effects' to be resolved, a compromise is usually found in *re-framing the original problem to focus on searching for a few multipurpose solutions*. Multipurpose solutions require high levels of concerted action. From a human perspective, this means concept developers need to have a basic understanding of all disciplines involved in the project to be able to explain what they wish to achieve to analysts. At the same time, analysts need to have a good understanding of this very early stage of the design process to be able to provide appropriate evidence for decisions to be made. Moreover, they also need to understand the different specialisms involved in the design process so that their solutions do not conflict with other types of building performance. In this context, digital tools can be seen as a risk to the achievement of multipurpose solutions because they are heavily specialised in terms of performance assessment. This yields useful questions for design teams: What is the right balance between the use of digital tools and non-digital expert knowledge within the design process? What are the different types of knowledge that need to be in place to enable the emergence of multipurpose solutions?

COMPUTER SIMULATION AND HAND CALCULATIONS

One of the groups presented an interesting *combination of repertoire recall with hand calculations and some carefully crafted computer simulations*. This balanced combination shed light on the fact that the conceptual design stage is always populated by some uncertainties that have a significant impact on the generation of evidence. If a large number of assumptions is necessary either to support specific decisions or to assess them, simulations might be seen as unnecessary or even misleading. In this sense, the overfamiliarity of the data analyst with specific simulation tools might be dangerous if it does not lead to the questioning of uncertainties, whereas the questioning of uncertainties can lead to the complete rejection of simulation tools, either in favour of hand calculations and/or in recalling past solutions from the practitioner's repertoire.

Either through simulations or not, the need to produce evidence to support or test regenerative design decisions was seen as fundamental in all design teams. This paper raised a set of considerations concerning the production of evidence and the way it is currently integrated throughout the design process. It has shown that there are potentially two different types of evidence to be considered: Evidence to enable concept developers to make decisions, and inspirational evidence to expand the search in the design solution space. It demystified the idea that evidence necessarily needs to come from digital simulations but that it does require expertise to be produced because it includes not only using simulation tools but also judging when they are effectively necessary. This paper proposes that specialisation can add to the design solution if all parties involved are reasonably knowledgeable of the different types of performance involved and are aware of the inherent uncertainties in the early design stages. The paper concludes that further thinking is needed concerning how different types of expert knowledge can effectively be used to produce the necessary evidence required in the regenerative design.

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THE TOOL(S) VS. THE TOOLKIT: THE HIERARCHICAL KIT

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Part I of The Tool(s) vs. The Toolkit [1] laid a foundation of five principles for designing and selecting for software to act as a part of an integrated toolkit instead of a single, isolated tool. It also presented a case for why an integrated toolkit is necessary for the building industry to reach the full potential of environmental modelling in its design workflows. Perhaps most notable among the arguments raised in Part I is that monolithic, isolated tools often hinder the learning process of the modeller and can prevent him or her from reaching a deeper understanding of the underlying components and assumptions of a computer simulation. Much like any technology, computer modelling can be misused, and when a modeller does not adequately understand the premises of a model they have built, they can end up making the wrong decision in a design process, ultimately detracting value rather than adding it. Modularized, connected, and open toolkits help defend against this situation by:

- enabling a learning process that can happen component-by-component,
- allowing for ease of cross-validation through connections to other tools, and
- supporting the mixing/matching of tools within the kit, thereby empowering modellers to answer new questions and test new creative solutions.

Accordingly, the original five principles of the toolkit published in part I constitute a doctrine found useful while developing the Ladybug Tools Legacy Plugins and to which they attribute much of the project's success. 'Ladybug Tools' collectively describe an open source project that was started in 2013 to support environmental design and education. Since its founding, a community of over 50,000 designers, engineers and building scientists has grown around it, adding code contributions and participating in the discussions of an online forum that receives an average of 3.5k pageviews per day. Of all the available environmental design software packages, Ladybug Tools is among the most comprehensive, connecting 3D CAD interfaces to a host of validated simulation engines, allowing designers to simulate daylight, building energy use, thermal comfort and several other environmental design parameters.

A HIERARCHICAL ASSEMBLAGE OF TOOLS

However, as time has passed since the publication of Part I, it has become apparent that there is at least one other principle that could have been followed in the development of the Ladybug Tools Legacy Plugins, which might have made them an even more useful toolkit. At the same time, many people have recognised the anachronism of a craftsperson wielding a large array of specialised tools and have rightly questioned how relevant toolkits will be in an economy that increasingly marches towards automation. There are good reasons why the modern economy possesses relatively few carpenters, blacksmiths, and artisans, and why many historic uses of toolkits seem to have been supplanted by mechanisation. However, upon closer inspection of the mechanisation process, it becomes clear that the tools of these trades are still very much in use in today's world, but it is just rare to find them wielded directly by an individual. Instead, they are integrated into much larger systems of tools that together obey a sixth principle of the toolkit - 'organise tools hierarchically.'

Deconstructing any contemporary automated tool quickly leads to the realisation that hierarchy within toolkits was a necessary pre-step for the mechanisation of today's industry. Whether one considers a 3D printer, a robotic arm, or a simple power tool, nearly all automated tools are composed of smaller components, and this has been the key to enabling the powerful capabilities that these devices endow (see Figure 27). However, it is difficult to distinguish between a monolithic tool that does not easily facilitate interaction with its components and a hierarchical assemblage of tools, which together can enable a specific task but can also be deconstructed into components that might perform different tasks in other situations. Both types of devices can endow automation capabilities, and both allow new users to understand some of the value that can be delivered by the device without knowing all of the components.

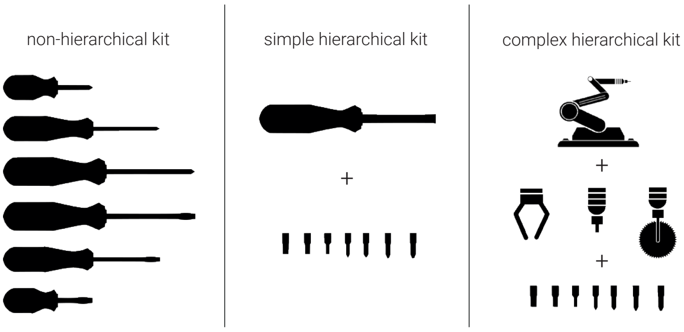

Figure 27
Example of toolkit hierarchy

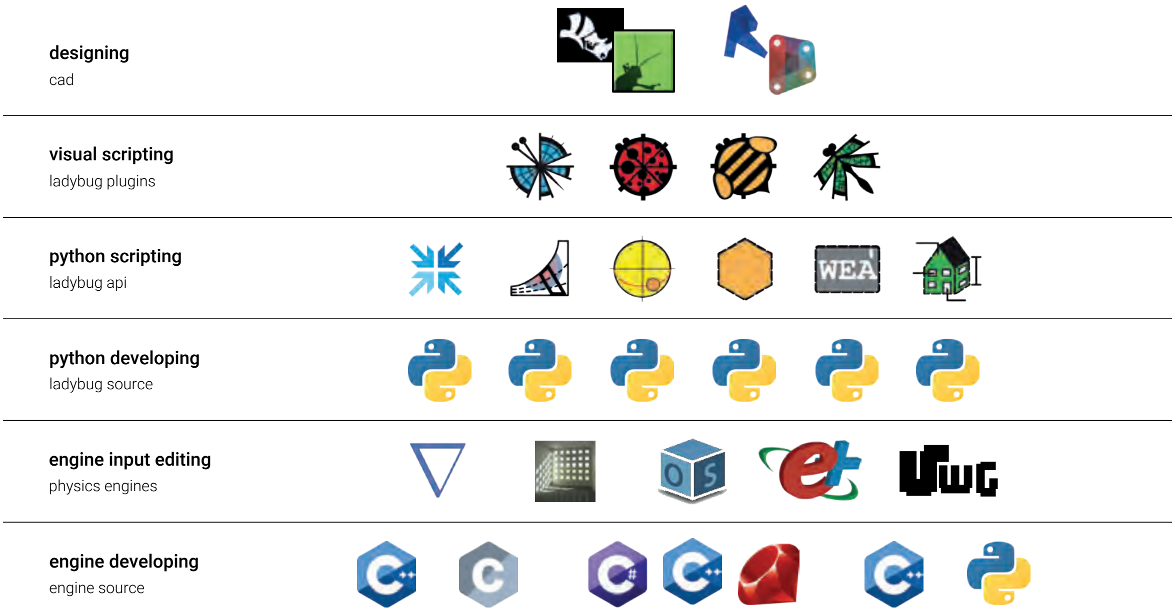

Figure 28
New Ladybug Tools [+] Plugins illustrating hierarchy as the backbone of an educational pathway.

THE EDUCATIONAL PATHWAY

However, only the hierarchical assemblage of tools sets up what one might call an 'educational pathway.' By this, we mean that one could start by operating a complete, fully assembled tool and then start working one's way down the hierarchy until they have mastered the individual components and can mix/match them to produce new types of custom assembled tools.

This analogy is useful for understanding why many of the deeper educational pathways of the Ladybug Tools Legacy Plugins failed to garner many followers. As an open source project built on top of open source physics engines, the Ladybug Tools Legacy Plugins naturally lent themselves to notions of users climbing down a deep educational pathway. Starting with basic knowledge of a computer-aided design interface, users could eventually end up with intimate knowledge of the source code within a physics engine.

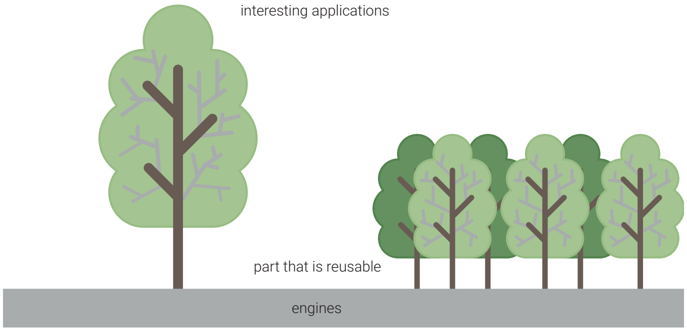

Figure 29
Hierarchy as the foundation of a software ecosystem

Yet, the past few years have made clear that all but a few users of the Ladybug toolkit go beyond visual scripting to engage with the Ladybug source code. In retrospect, we can understand that this situation resulted because the Legacy toolkit lacked sufficient hierarchy in its organisation. While individual visual scripting components may have been well documented with a clear organization in relation to each other, there was little hierarchy or documentation for the code that made up these components. The newer Ladybug Tools [+] plugins attempt to address this shortcoming by hierarchically organising source code into an Application Programming Interface (API) or a library of hierarchical modules that can be interfaced with before delving into the underlying code (Figure 28).

BUILD ON TOP OF EXISTING WORK

In addition to enabling users to climb down an educational pathway, hierarchical organisations of tools also enable progression in the other direction: they make it easier for others to build on top of one's existing work. Many of the most widely used software packages of today are organised much like a tree, where a strong trunk of reusable software infrastructure that possesses a clear hierarchy supports the interesting applications of the software and organisation (left of Figure 29). Yet, more often than not, software developers are so anxious to achieve an interesting new application that they end up re-making many of the underlying capabilities of other tools just to enable that one capability (right of Figure 29). This is done in lieu of working with others and collectively investing time to build a stable foundation upon which many capabilities can co-operate. Sometimes, the rush to reach a new application is for a good reason, and one could argue that the Legacy Plugins were built 'without a trunk' because the value of the software needed to be proven before its developers could invest time in building a strong foundation. However, as soon as an application is proven useful, one should quickly begin considering how a stronger foundation can be built, and how better integration with other tools can be achieved.

The new Ladybug Tools [+] libraries are organized in such a hierarchical fashion with modules built on top of modules in a manner that aims to be the reusable software infrastructure of many environmental design workflows. As one would expect, this new hierarchy is enabling the creation of a wide array of new interesting applications, including interfaces for other CAD programs, new types of environmental design studies, and the use of scalable cloud computing resources for large simulations. In spite of all of these tangible benefits, the Ladybug Tool still has much more to gain by continuing to embrace hierarchy - the sixth principle of the toolkit.

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A PLUGIN FOR URBAN VISUAL IMPACTS

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To qualify the experience of people in the outdoor public space, it is essential to determine the visibility of some details in the urban landscape. These can be crucial details, such as road signs, pleasant details, such as vegetation, or unpleasant details, such as advertisements. Many features that fall within pedestrians' visual field in an urban walk are located on buildings. The methodology presented here was originally developed to assess the visual impact of building integrated solar modules. The proposed workflow examines how to quantify the visibility of elements in urban contexts at the different planning scales, which can be used to drive fundamental decisions in terms of outdoor comfort, psychological well-being and cultural heritage protection.

Going for an outdoor walk in our cities to take fresh air, enjoy a panorama, view a monument or even shop and have a drink is a great recreational experience. Some features that come across our field of view, though, can be disturbing or irritating and engender a negative sensation. Imagine you are sitting in a square in front of a town cathedral, and suddenly a large truck stops right in front of you to deliver supplies to a neighbouring bar. After a while, sun reflections from a solar panel installed on a surrounding rooftop hit your eyes; then you stand up and look for the post office sign while walking down a commercial street, but you cannot find it in the jungle of shop brands. You are facing the impact of visual pollution.

VISUAL POLLUTION

Visual pollution is a combined effect of confusion, disorder, and a mix of different objects and graphics in the environment. Examples are outdoor advertisements, billboards, street furniture, road signs, waste collection points, parked vehicles, hydraulic fixtures and tubes, wires and cables and mobile communication antennas. Especially in urban environments, these items can disturb observers' attention. Beyond their emotional and psychological influence, some of these features can be harmful or dangerous: lighting and blinking features can induce disturbance and epilepsy seizures; potential glare sources like artificial lighting emitters and highly reflective surfaces like mirrors are distracting for drivers.

cumulative viewshed

invisible cells
□ 0
visible cells
(deciles of times seen)
🟨 1 - 2
🟨 2 - 5
🟨 5 - 9
🟧 9 - 14
🟧 14 - 20
🟥 20 - 28
🟪 28 - 38
🟪 38 - 52
🟪 52 - 75
🟦 75 - 78

Figure 30
Carouge, Geneva, Switzerland. Cumulative viewshed per deciles of « times seen ». Elaboration of CC data from Système d'Information du Territoire à Genève – SITG.

Several visual impacting elements, including the advertisement, can be integrated into building envelopes, or in other words, rooftops and façades. As such, they assume particular relevance in the framework of regenerative design. In particular, solar modules for photovoltaic or thermal energy production are often overlaid on the exposed surface of buildings, increasing their reflectivity and the consequent glare induction risk. Assessing the visibility of these elements from the public space in the design phase may help prevent uncomfortable situations and allow estimation of a reasonable application range that meets the broadest social acceptance by the local context. In this framework, extensive work has been done to elaborate a scale-adaptive methodology to assess visibility in urban areas. The territorial scale and the district level are covered, with increased detail at the group of buildings stage. As such, a specific index was determined at each scale for inclusion in a multi-criteria model. At the broader scale, visual interest and viewshed based indicators are proposed. At the district scale, photometric models and ray-tracing techniques were explored to mimic human vision and identify the perceived areas of building envelopes that can potentially host solar modules.

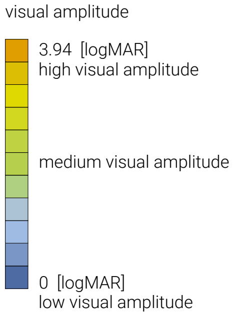
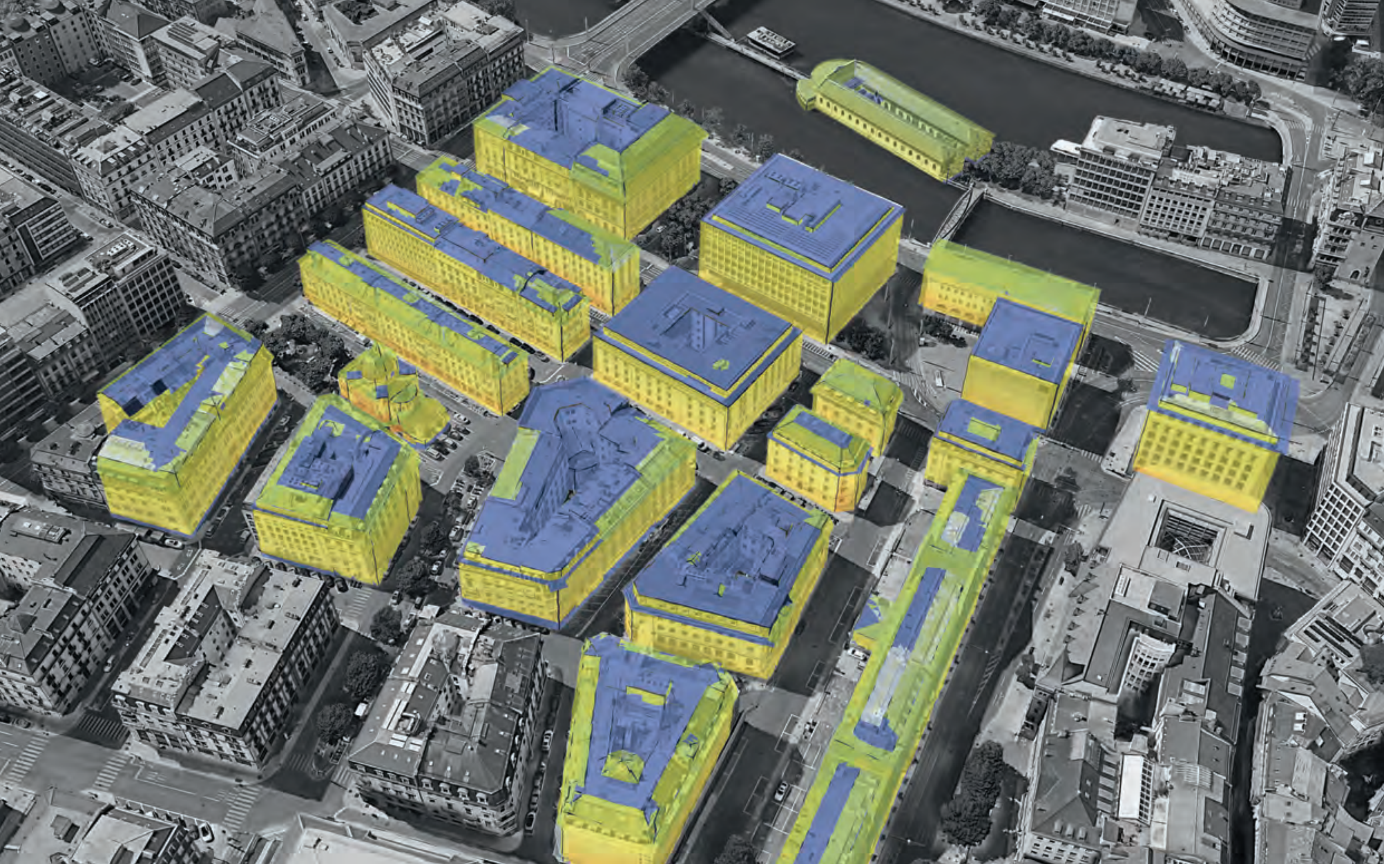


Figure 31

Hollande district, Geneva, Switzerland. Visual amplitude index of the building envelopes. Elaboration on CC data from Système d'Information du Territoire à Genève – SITG. Background photo from Google Earth ©

DIGITAL ELEVATION MODEL

The urban fabric emerges at the scale of urban development, and blocks of buildings can be discerned individually. Their visibility is regulated by geometric factors and reciprocal obstructions, depending on massing articulation, topography and depth of the urban canyon. At the scale of urban development, counting the number of vantage points on the public space that have an unobstructed view of a building envelope fraction seems adequate, instead of investigating the physical perception from each viewpoint, which would be more rigorous. As such, the number of visually connected locations to façades and roofs is computed in a GIS environment. A suitable indicator for this purpose is the 'cumulative viewshed' (also known as 'times seen'), which counts the number of times each building surface is intercepted by a visibility ray coming from several points sampled on the public space [2]. A digital workflow to place the viewpoints with a given spacing distance on the road network and extract the building elevation information from the Digital Elevation Model (DEM) has been set-up in GIS for this scope. In Figure 30, the viewshed map of a district in Geneva, Switzerland shows at a glance which buildings are more exposed to public view and therefore deserve more careful design interventions. Buildings surrounded by open space, squares or river shores can be visible by up to 100 times the viewpoints than those arranged in courtyards or dense parcels.



The assessment procedure becomes more detailed when zooming in to the building level. Occlusion from vegetation and urban furniture (lamps, benches, signs …) generates non-uniform shades of visibility of envelope surfaces: different tilts and volume intersections with chimneys, terraces, etc. affect the global perception of a surface fraction beyond the discrete attribution of 'visible'/ 'invisible' from a given set of locations. Physical factors such as visual acuity and contrast should be taken into account for each envelope surface feature made in the previous stage. As such, visibility rays are projected from a grid of scattered pedestrian eye-level positions to building surfaces, as a lighthouse would do with its spotlight [3],[4]. Visual stimulus is quantified as the solid angle produced by a target surface, representing a possible solar module array, on the spherical visual field of each viewpoint about its perceptual threshold. This ratio can be converted to a metric everyone is familiar with; the LogMAR visual acuity measure: it is issued from the typical test of 'reading the characters' performed by an optometrist. The entire calculation procedure is carried out in Grasshopper for Rhino by combining vector tracing components and by decomposing the target surfaces in triangular meshes.

THE VISIBILITY INDEX

Figure 31 shows the visibility index, here referred to as ‘visual amplitude’ (VA), calculated on a 1.50 m resolution mesh on building surfaces of the ‘Hollande’ district in Geneva, Switzerland. Contributions from a set of viewpoints are averaged to get a mean visual amplitude index per mesh face. It can be noticed how flat roofs are non-visible, especially from narrow streets, and façades are more visible than tilted roof pitches. The methods mentioned above are useful to quantify visibility on an objective basis and can be matched with solar energy generation potential for planning purposes. Other possible practical applications include the optimal placement of outdoor advertisements, the quantification of vegetation presence within a view and the establishment of maximal brightness thresholds for luminous signs. As for pedestrian comfort, combining the absence of glary and polluting luminous sources with the presence of natural elements in the visual field can enhance the ‘biophilic’ connection with the environment as well as increase the outdoor psychological well-being. Sky view and ‘visual openness’ should be evaluated at this scale to preserve the meteorological influence on human chronobiologic cycles. Moreover, a sufficiently wide depth of view is linked with the human instinct of safety and the opportunity to escape the area, in this case, a dense urban space.

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ADVANCED SOLAR ENVELOPE GENERATION

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Daylight is the source of illumination most appreciated by occupants of buildings for its capacity to render objects in their natural colours, contributing to the comfort of vision and the creation of shade and contrast between surfaces, thus improving architectural quality [1]. Access to natural light also provides the proper perception of day-night alternation and exposure to luminous stimuli, which can improve humans' physiological well-being through correctly entrained circadian rhythms [2]. Among the various components of daylight, direct solar radiation can offer significant benefits for its quantity, quality and distribution potentialities.

Building standards relating to solar access for occupants in new and existing premises exist in different countries to ensure the healthiness and comfort of dwellings. They require minimum hours of direct sunlight through room windows per day of the indicated period regardless of sky cover (e.g., in Germany, Regulation DIN 5034-1 states that every apartment must have at least one window receiving a minimum of 1 hour of direct sunlight on 17th of January and 4 hours on 21st of March and September). Designers often overlook direct solar access standards because they are challenging to take into account without appropriate design tools or, in some cases, not implemented into strict regulations by authorities, thereby compromising the well-being of building occupants.

SOLAR ENVELOPE

The solar envelope method devised by Ralph Knowles at MIT enables architects and planners to take into account required direct solar access on existing surrounding facades during the schematic design phase by determining the maximum height and massing that the designed buildings cannot exceed [3]. The inputs for the solar envelope calculation are the solar azimuth and elevation angle at the required hours; the borders of the plot of the new development; the distance of surrounding buildings; and, the height of the shadow line on surrounding facades. Depending on the plot shape and surrounding building distances, the solar envelope has a variable, irregular pyramidal shape.

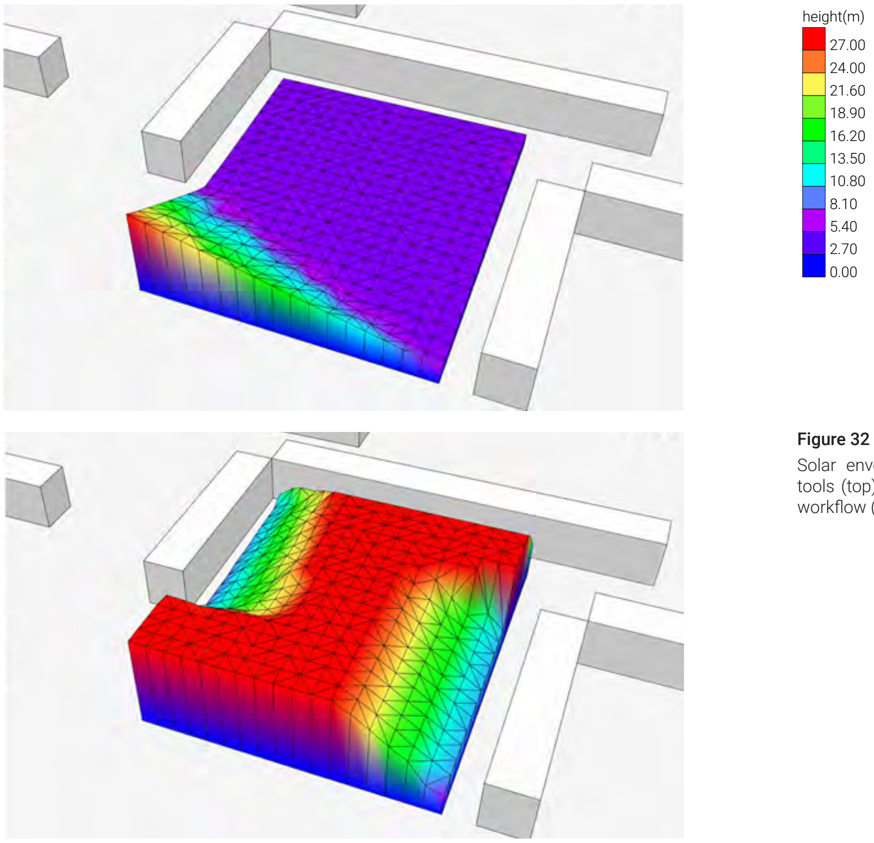
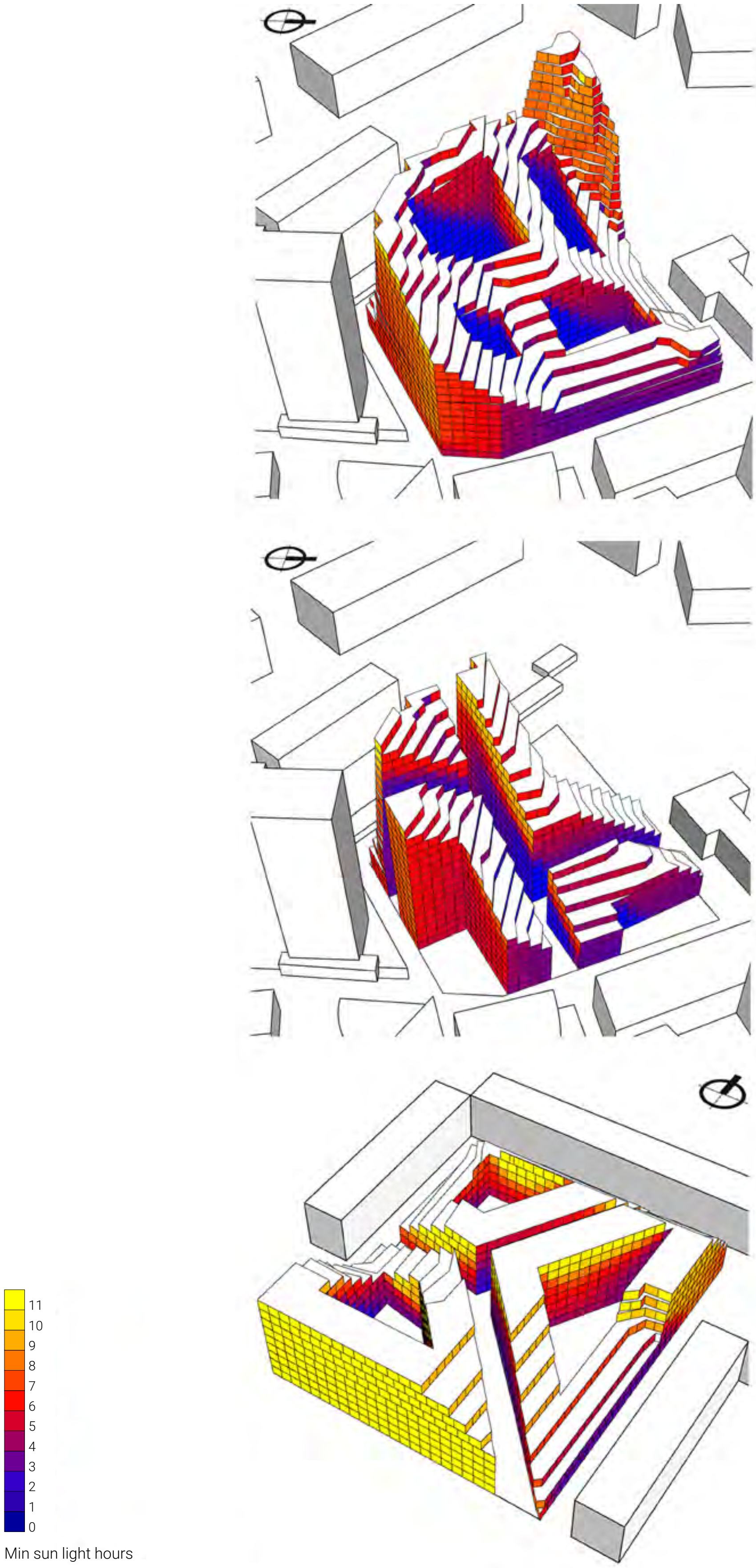


Figure 32
Solar envelopes generated with existing digital tools (top) and with the proposed computational workflow (bottom).

Figure 33
Sunlight hours analysis on building clusters located in urban areas in Tallinn and shaped by a solar envelope.

DIGITAL TOOLS

Digital tools - such as Ladybug Tools and DIVA for the parametric design software Grasshopper - can be used to generate solar envelopes. The main settings required are location latitude, plot outline, the location of shadow lines, analysis period and daily start-end hours during which direct solar access needs to be guaranteed on surrounding facades. While the mentioned tools are the most advanced at present, they have limitations. For example, they do not take the surrounding environment into account, making them inefficient when used in urban environments, and the start-end hour input makes them unusable for standards that require quantity of hours, such as required by the mentioned German Regulation DIN 5034-1, or percentages of hours of insolation, required by the Estonian daylight standard presented in the next section [4].


11
10
9
8
7
6
5
4
3
2
1
0
Min sun light hours

ADVANCED COMPUTATIONAL WORKFLOW FOR SOLAR ENVELOPE GENERATION

A computational workflow and a novel method were developed to overcome the mentioned limitations and efficiently generate solar envelopes for urban environments, and for the time input of different standards. The current digital tools used to create solar envelopes are not effective when applied to the 'right to light' requirement established by the Estonian daylight standard [4]. This standard requires that existing facades are not deprived of more than 50% of their windows' actual direct sunlight hours. This applies to each of the days included in the period ranging from the 22nd of April to the 22nd of August.

To improve the capabilities of the existing tools, a workflow was developed based on the design of an algorithm using Grasshopper and the environmental design plugin Ladybug Tools [5]. The algorithm is composed of two main sections. The first section divides the facades surrounding the plot by using sampling and computes if each sample receives direct sunlight, and during which hours of every day of the required period. Sun vectors define the hours. The second section of the algorithm calculates the required 50% of sunlight hours. The designer can thus select the sun vectors with the most significant solar altitude, which provide primary solar radiation.

The selected sun vectors are used to generate one solar envelope for each sample. The workflow guarantees that the windows of the façades receive the required solar access, thereby creating larger solar envelopes in urban environments (Figure 32). The workflow can be customised to different time ranges and various national standards. The workflow was used to generate building cluster forms that optimise direct solar access and ponder the buildable floor that is allowed in Tallinn [6] (Figure 33).

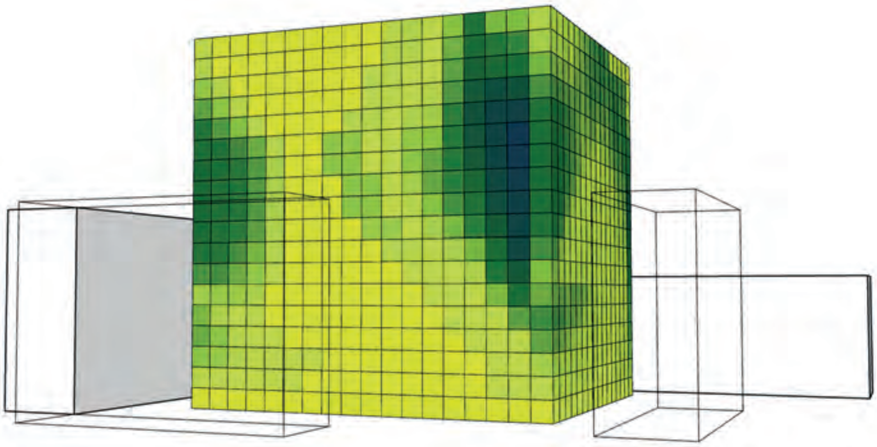
Figure 34
Voxels are indicating the quantity of direct solar access hours blocked on the surrounding windows.

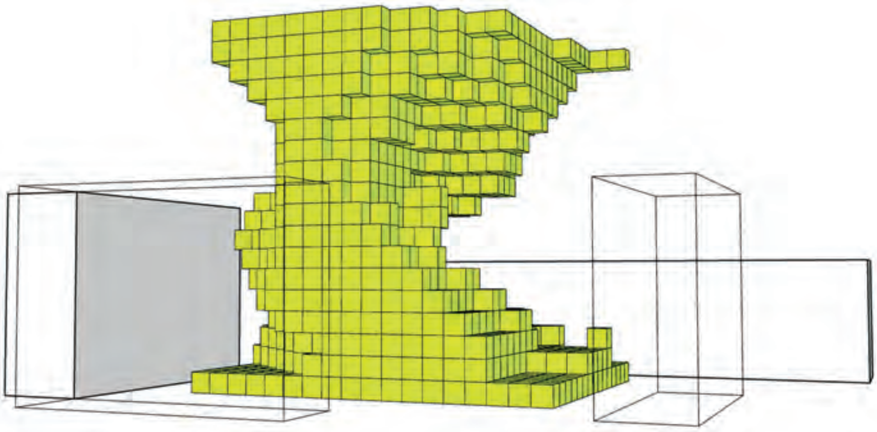
Figure 35
Solar envelope generated with the new subtracting method.

EFFECTIVE SOLAR ENVELOPES IN DENSE URBAN AREAS

Building on the advanced workflow presented, a novel method was developed to generate particularly useful solar envelopes in dense urban environments such as city centres [7]. It is a subtractive method based on the culling of three-dimensional cells obtained by subdividing a built volume by extruding the plot outline (see Figure 34 and 35). After having selected the required quantity of sun vectors (sunlight hours), the algorithm tests for intersections between all the three-dimensional cells and the sun vectors raytraced backwards from each window of the facades surrounding the plot.

Figure 36
Experiment directly translating the mass of a solar envelope generated with the novel method into a building form.





Each cell is thus transformed into a colour coded voxel. This colour gradient reflects the quantity of direct solar access hours that it blocks (Figure 34). This method enables the option to eliminate all the blocking cells and to keep only those that allow the required 50% on all the surrounding windows (Figure 35), or a larger quantity of cells (allowing for increased solar access of surrounding dwellings and related occupant well-being), or a portion of them, keeping those with minimal impact (i.e., those that block only a few hours of direct solar access for the total number of surrounding windows during the entire period of 123 days). In this way, the designer can evaluate the size and shape of the solar envelope in the process of negotiation between form and solar access requirements.

The subtracting method allows designers to perform direct solar access analysis on the vertical faces of the solar envelope to provide information useful for the floor plan layout of new buildings. The method allows determining the maximum size of high-rise buildings in dense urban environments through the addition of buildable mass in the upper part of the solar envelope (Figure 36). Giving architects and planners the possibility to design more efficient buildings and comfortable urban environments, the proposed methods contribute to the regenerative goals of a healthy city with maximum solar access for dwellers and support social and physiological well-being. Furthermore, the methods can be used for urban brownfield areas, highlighting the possibility for preserving pristine land and the biodiversity that populates peri-urban areas. Altogether, the tools could be used to promote citizen health and local biodiversity, thereby increasing the healthy state and the quality of life in contemporary cities.

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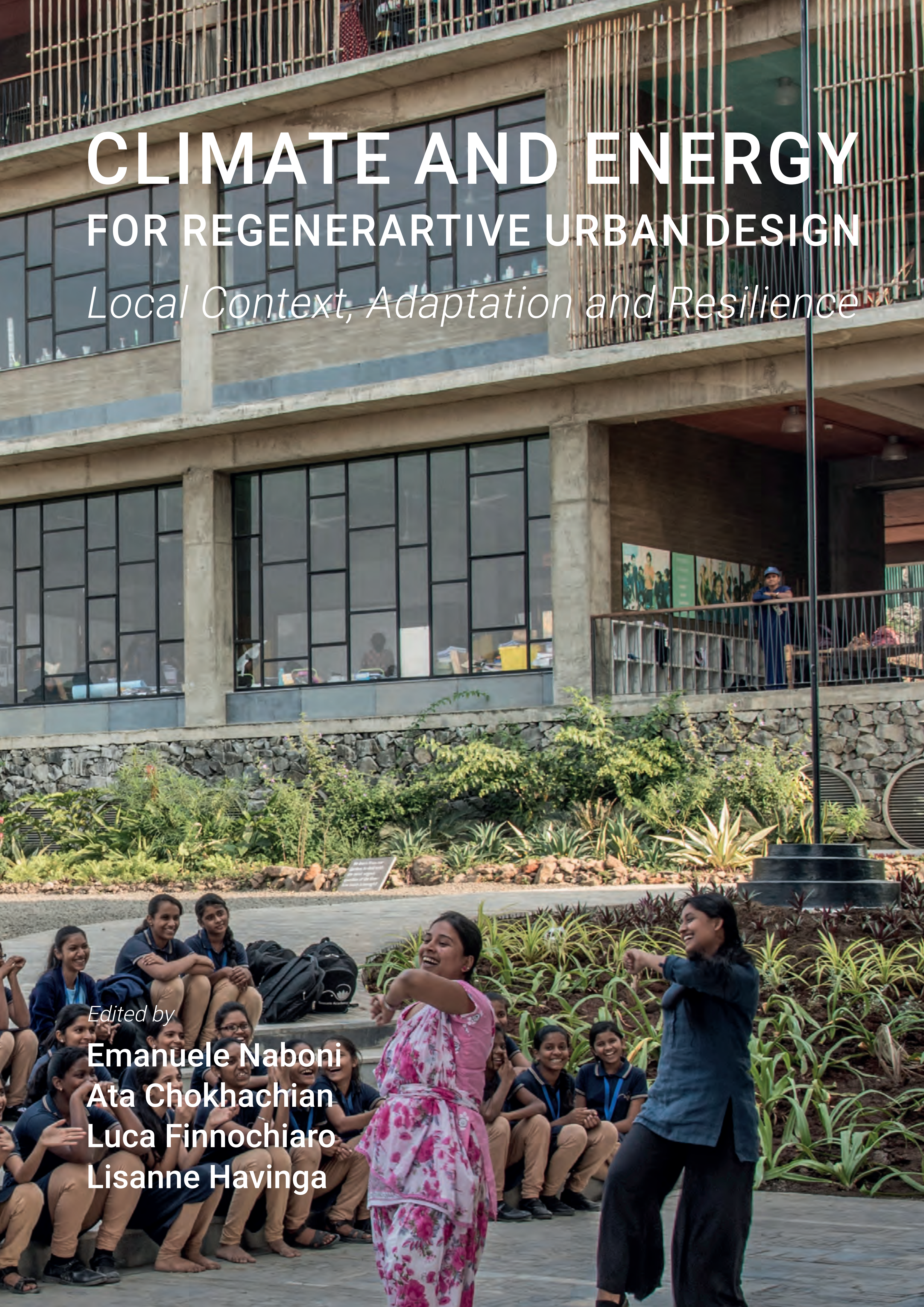

CLIMATE AND ENERGY
FOR REGENERARTIVE URBAN DESIGN
Local Context, Adaptation and Resilience

Edited by

Emanuele Naboni
Ata Chokhachian
Luca Finnochiaro
Lisanne Havinga

Chapter Cover Image - The Avasara Academy

The Avasara Academy (as presented in *'Regenerative Nature-Based Solutions and Technologies'* by Maria Beatrice Andreucci) is a residential school campus in a rural village in India. Passive-adaptive strategies were implemented to achieve thermal comfort in the hot and humid Indian climate. This includes strategic program placement, climate responsive massing, locally sourced wooden shades, screened and shaded outdoor living areas, and a purposely-designed natural airflow which benefits all functional spaces, contributing to a year-round comfortable learning and living environment

Courtesy of Case Design © Ariel Huber

CLIMATE AND ENERGY FOR REGENERATIVE URBAN DESIGN

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PATHS OF URBAN ADAPTATION TO CLIMATE CHANGE

Emanuele Naboni *KADK Copenhagen, Denmark*

We are bombarded with statistics about the future of cities highlighting that half of humanity — 3.5 billion people — live in cities today, and this number will continue to rise to 5 billion people by 2030 [2]. These figures make impressive headlines for stark reports on the effects of urbanisation, but they are meaningless without action to transform cities into inspiring-healthy environments with outdoor comfort, clean air, connections to nature and energy positive buildings linked by a network of green energy. While cities are at the heart of the problem, they also provide dynamics that can be used to develop solutions. Cities are hubs for commerce, culture, science, productivity, social development and new ideas, which must be harnessed to address some of the greatest issues facing humanity, like climate change, health and poverty, [1] as also stated by the UN SDG #11.

URBAN HEAT ISLAND

As the urban population increases, issues related to climate change are becoming tangible. Climate change affects average patterns, as well as the manifestation of extreme and more frequent weather events, such as heat waves [3]. In the near future, it will have an even greater impact in urban environments, leading to environmental stresses on urban infrastructure, especially if business is continued as usual. This condition is exacerbated in urban areas where spaces are warmer than surrounding rural areas. The densification of cities and the use of artificial materials has indeed led to higher temperatures. Concrete, asphalt and steel reduce the city albedo (the thermal reflectivity of surfaces), and the absorbed heat is retained in place by thermal mass.

Almost 40 years ago, Oke defined the three main causes of changing climates within cities [4]; these are:

- the interception of short- and longwave radiation between buildings
- the reduced heat emission in longwave radiation due to reduced sky visibility
- the increased storage of sensible heat in building materials [3].

The subsequent installation of indoor air conditioning systems increases the overall urban temperature (heat is extracted by indoor spaces and emitted in the street), creating a circular negative effect in which the energy demand and the greenhouse related emissions continue to grow. These adverse circular effects determine the so-called Urban Heat Island (UHI).

To offer sufficient living space in cities to accommodate the constantly increasing numbers of inhabitants, more and more inner-city green spaces will continue to be replaced by buildings with no regard for UHI effects or for the global temperature rise [5]. Implications are local and global, calling for affordable and scalable strategies to curate the issue of UHIs as demanded by the UN SDG #13, which focuses on climate change.

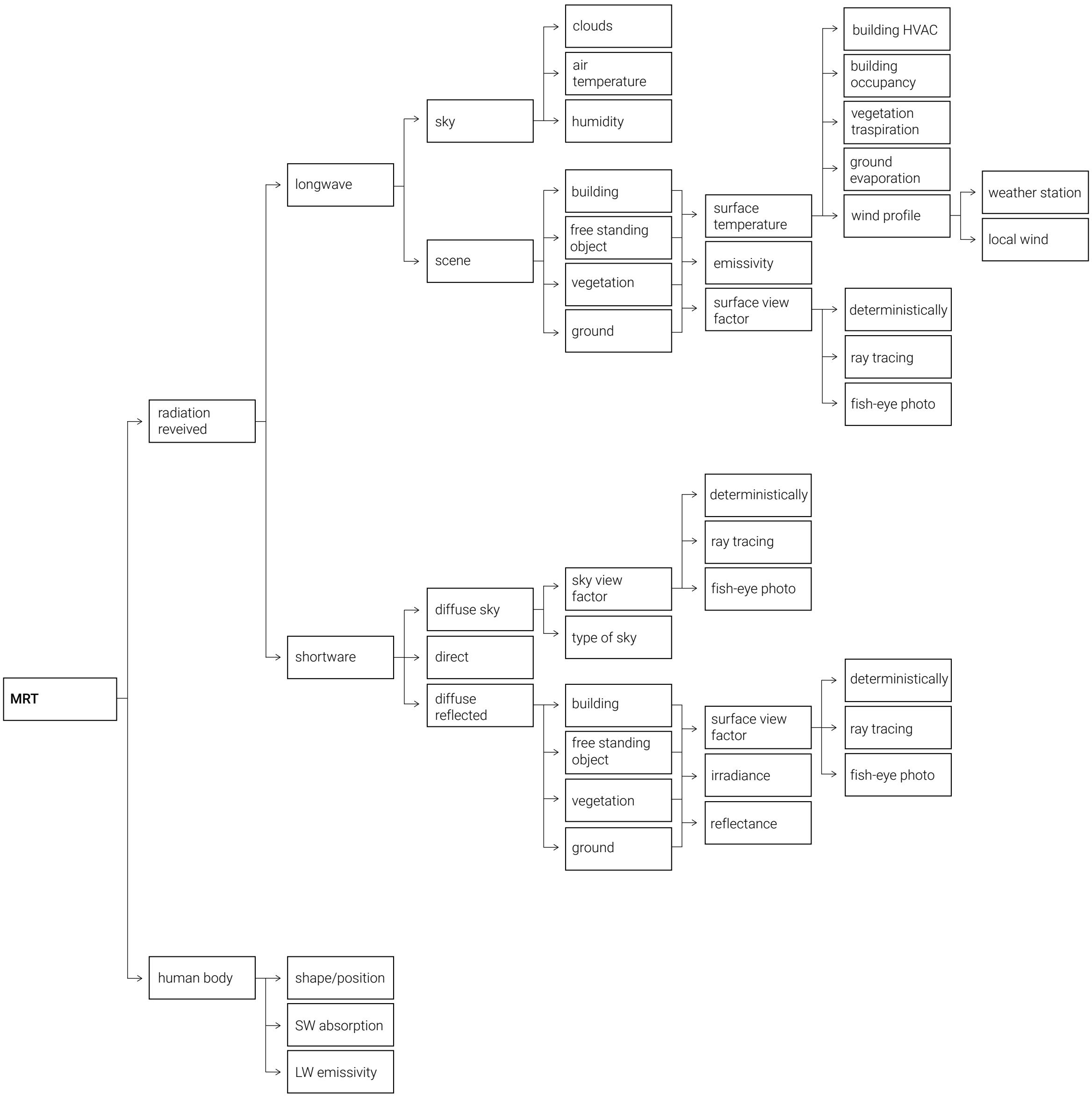
RESTORING OUTDOOR COMFORT

Non-favourable urban microclimatic conditions limit outdoor life, socialising and relationships between people in good health. Furthermore, evidence of health-risks and increased mortality rates among the elderly and people suffering from cardiovascular and respiratory problems have been widely reported as a function of UHI effects. For example, warmer days and nights along with higher air pollution levels can contribute to general discomfort, respiratory difficulties and illness, heat exhaustion, and heat-related mortality due to lack of night ventilation and trapped heat in the city. As such, countermeasures to UHI effects have to be sought and implemented as soon as possible.

It is known that design choices, such as the form and the materials of buildings and open spaces, alter local thermodynamic phenomena, which in turn influence outdoor thermal comfort. The outdoor thermal comfort, as opposed to the indoor one, is ever changing, with wide spatial and temporal variability due to weather changes. Silvia Coccolo thus introduces, in the first section of the chapter, a set of strategies that modify outdoor thermal comfort and improve the thermal environmental quality of cities. Outdoor comfort can be either digitally modelled or measured on site [6] and, in the last decade, the scientific community has become increasingly interested in the topic and has encoded a few modelling tools to support the simulation of microclimatic conditions. The potential users of microclimatic modelling tools are often confronted with a lack of specific information about their calculation and applicability to the type of contexts and climates (Figure 1)

Figure 1

The graphic shows the parameters affecting outdoor comfort and the simulation methods' possibilities. Each simulation tool adopts different simulation methods. Providing designers with clear information about the calculation methods help them in selecting the appropriate simulation tool according to the site type.


MRT
radiation reveived
longwave
sky
clouds
air temperature
humidity
scene
building
free standing object
vegetation
ground
surface temperature
emissivity
surface view factor
building HVAC
building occupancy
vegetation traspiration
ground evaporation
wind profile
weather station
local wind
deterministically
ray tracing
fish-eye photo
shortware
diffuse sky
sky view factor
type of sky
deterministically
ray tracing
fish-eye photo
direct
diffuse reflected
building
free standing object
vegetation
ground
surface view factor
irradiance
reflectance
deterministically
ray tracing
fish-eye photo
human body
shape/position
SW absorption
LW emissivity

Outdoor comfort simulation tools and their capabilities have been assessed in previous research by the author [7, 8], revealing that the most commonly used tools in the research domain are ENVI-met, SOLWEIG (Solar and Long-Wave Environmental Irradiance Geometry), the RayMan model, and the UTCI calculator. They have been applied to compute climatic conditions that range from urban canyons to city scale.

Among these tools, just one, ENVI-met, could represent more complex 3D geometry. However, in the last five years, two - urban planner and architect oriented - tools have been refined to include outdoor comfort modelling. These are also based on 3D models: CitySim Pro and the Ladybug Tools suite. In summary, CitySim (Figure 2), ENVI-met (Figure 3), and Ladybug Tools are of interest to designers and are the ones more referenced in this chapter.

When designers are working on the modelling of the outdoor thermal comfort of a specific location, it is essential to understand how pedestrians are currently experiencing it. The understanding of human physical, psychological and physiological adaptation to the environment could be modelled, but providing onsite information via local measurements and comfort surveys is the most valid information. To mitigate the impact of heatwaves in cities, an interesting direction is the employment of wearables to create human-centric knowledge. Using an Internet-of-Things approach, the aims should be to develop wearable weather stations, obtain unprecedented real-time climate data, and determine the complex impact of urban heat on humans.in cities. The expected outcomes of research of this kind are crowdsourcing of urban climate and heat stress, and evidence-based guidelines to build climate-smart cities. Such outcomes would provide significant benefits to planning and environmental health.

For that reason, Ata Chokhachian explores the potential of integrating biometrics, surveys and local climatic data to determine the Universal Thermal Climate Index (UTCI), the most accepted metric for outdoor comfort. Released in the summer of 2009 as a result of COST Action 730, the UTCI is thermophysiologically significant in the whole range of heat exchange; valid in all climates, seasons and scales; and, useful for key applications in human biometeorology (e.g. daily forecasts, warnings, regional and global bioclimatic mapping, epidemiological studies, and climate impact research). Furthermore, it is independent of a person's characteristics (age, gender, specific activities, etc.). As such, only tools and application cases that refer to UTCI are discussed in this chapter.

Figure 2

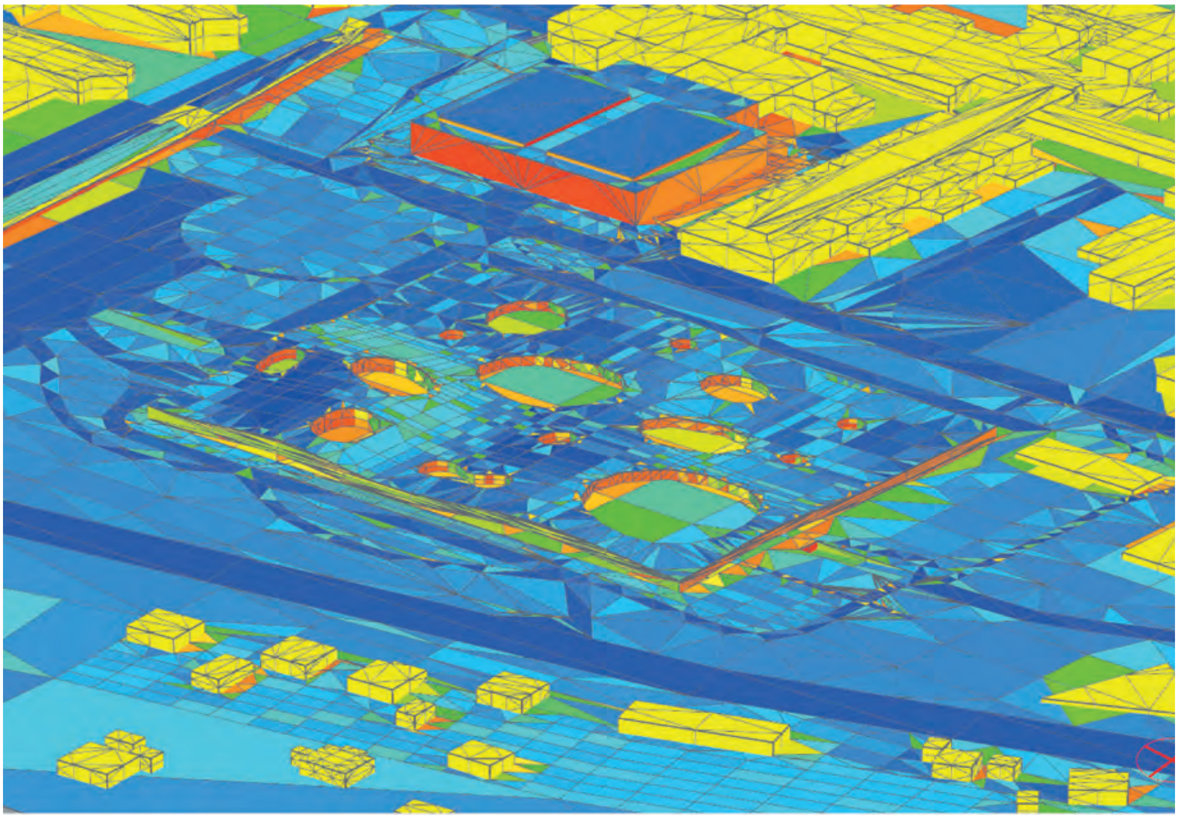
Longwave net irradiation simulated with CitySim for the EPFL campus in Lausanne on a summer day. Longwave radiation yields infrared radiation that causes people to feel the heat. Longwave includes the heat energy emitted by all built environment objects, such as buildings and trees, even those in shaded areas without incident solar radiation. Radiation is influenced by objects, trees, and buildings' architectural characteristics such as sizes, allocations, shapes, and materials

Wh/m²

🟥 15.2
🟧 -111.9
🟩 -239.1
🟦 -366.2
🟦 -493.3

RE-GREENING OF THE CITY

UHIs and the increasing reduction of green areas in the city have massively decreased the environmental quality of cities. This may discourage citizens, especially the elderly, from spending time outside, making it imperative to re-focus on intervention to obtain microclimate that favours and promotes people's health and wellbeing. Greening of cities is a key strategy from many sides. It improves urban inhabitants' psychological wellbeing, helps with flood protection and noise reduction. It positively influences air quality via CO2 mitigation and outdoor thermo-hygrometric comfort. Besides, greenery is the only known side-effect-free solution against heat in cities [9].



In terms of SDG's, greening in urban areas is addressing several of the 17 objectives and can contribute to achieving them in the long term. These include not only the direct contribution to climate action, but also a significant impact on halting biodiversity loss through increased urban biodiversity, and an increase in healthy living conditions in cities through the additional binding of air and water pollutants. According to UN SDG #3, nursing healthy lives and promoting well-being for all is central to building prosperous societies. From a broader perspective, debating urban greenscapes, Maria Beatrice Andreucci consequently links these topics in a section that focuses on the potential of natural elements to increase human comfort via a series of demonstration cases from Transolar and Daniele Iori.

Improving urban inhabitants' access to green spaces and water is important for the 'urban agenda'. A few cities are already engaged in adaptive actions being the 'first responders' to climate change. Extreme climatic events change the cycle of water, and cities, such as Copenhagen, are adopting climate adaptation via the design of green areas that leverage the ability of soil to retain water. To facilitate such process, Christian Kongsgaard develops and presents here a new Grasshopper plugin that offers users the capability to dynamically quantify the amount of collectable water, and determine how water and humidity will affect the local microclimate.

NATURE-BASED SOLUTIONS

The rapid urbanisation around the globe during the last five decades has come with a heavy price to the environment. With increasing awareness about this issue, cities are looking at Nature-Based Solutions (NBS), such as green roofs and green walls, as a tool to mitigate environmental degradation. Unlike other 'green' sectors such as solar photovoltaic or biofuels, NBS adoption is not driven by national-level policy measures, but entirely by city-level priorities. The value proposition against competing technologies has been a major barrier to their adoption, as, according to many, competing technology exists with arguably a better cost-to-performance trade-off.

Installation costs for green roofs and green walls are excessively higher than technologies such as coatings that offer thermal insulation benefits, photo-catalytic coatings that remove pollutants from ambient air, and rainwater harvesting tanks that reduce the storm-water volume. Therefore, cities or building owners evaluating technologies to address a single environmental issue will be likely not to adopt green roofs or walls.

Only cities looking at all possible environmental benefits of green roofs and wall designs have supportive policies in place. This is the case in, among other cities, Vienna, Copenhagen, Beijing, Shanghai, Tokyo, Sydney, New York and Toronto. The section of Vincenzo Costanzo casts some light on this specific issue by proposing a comparison between cool roof and green roof technologies when applied as passive cooling strategies for existing cities, and looks more specifically at the single building applications.

IMPROVING AIR QUALITY

For the majority of people in the 20th century, the futuristic city was living in a park-like setting as described in the *'Garden City'* or *'Radiant City'*, once so cherished by architects and planners. Yet since then, real cities have been fashioned with asphalt, brick, concrete and mechanical systems, becoming pollution 'hot spots'. Cities worldwide emit 80% of global greenhouse gas emissions and pollution. 91% of the urban population is being exposed to air pollution, which is considered hazardous to health by the World Health Organization [10].

Pollution affects not only the urban fabric but also ecosystems globally, impairing vegetation growth and harming biodiversity. The main issue is related to developing economies. However, Europe is still central to the issue, where unsatisfactory regional and urban planning has generated polluted cities [11]. As UHIs increase, so does the pollution in cities. COx, SOx, NOx and particulate matter concentrations are exponentially increasing.

It is argued here that urban planners and architects need to revisit cities forms, streets, landscapes and buildings as active solutions to inspire sustainable living and combat poor air quality. Some significant modifications of these kinds are already adopted by some cities that seem to return to *'cities-overgrown-by-greenery'* scenarios. The abandonment of industry in many inner cities left large areas available for new urban forms and type of buildings, greens, parks, urban farms and other sorts of venues with a more exotic horticultural theme. In recent years, those spaces have been reclaimed or built over. Both the London Olympic Park and the New York High Line are well-known examples.

The contribution of Jakob Strømann-Andersen, drawing from the international experience of the Danish Office Henning Larsen, establishes a further link between the built environment, air pollution and outdoor thermal comfort. Several case studies are here introduced and translated into a set of design recommendations useful to all the practitioners of the built environment.

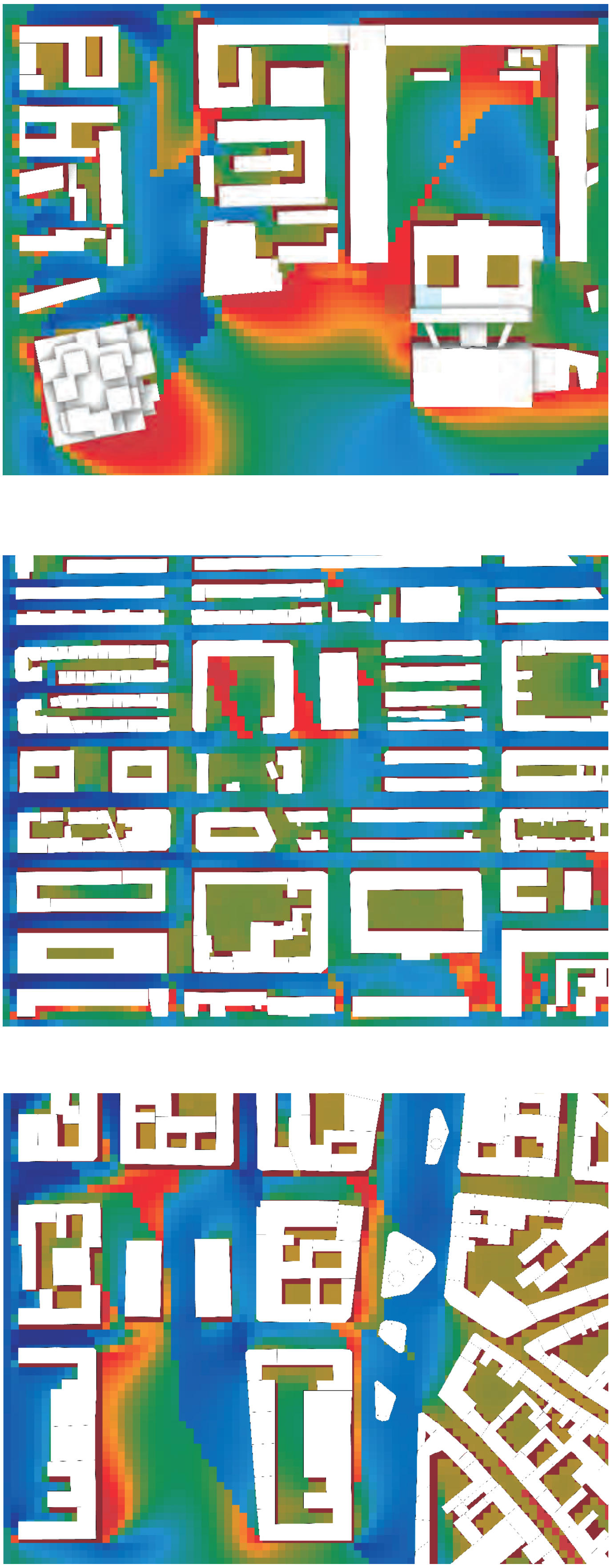


Figure 3

Studies of the influence of urban morphology and materials on outdoor comfort in Copenhagen. Students' work at CITA workshop (teachers Emanuele Naboni, Jonathan Natanian, Daniela Maiullari, Daniele Santucci, Paul Nicholas)

CLIMATE CHANGE, ENERGY DEMAND AND ENERGY POVERTY

Climate change is leading to more building emissions that, in turn, further contribute to more climate change, in a negative yet unstoppable loop. Today, 60 per cent of total global greenhouse gas emissions are from buildings [2], and climate change is alarmingly leading to an increase in this percentage. Climate change at large, and Urban Heat Island effects locally, are thermally stressing the building stock, resulting in an increase in energy consumption used to cool internal spaces. For instance, at mid-latitudes, the energy demand for heating has reduced by 25% but has increased by 15% for cooling [12], thus leading to further energy use and emissions. More precise patterns of future energy demand change about climate change are thus offered in the contribution of Emanuele Naboni, and the need to return to bioclimatic design is here emphasised.

The interconnections between climate change, UHI effects, and building energy demand are mutual and not easy to comprehensively characterise due to several trade-offs. It can be forecasted that if passive cooling strategies are not implemented, this will lead to a major rise in energy costs that affect everyone, but especially poor people. More recently, the term ‘energy poverty’ has arisen to describe the point at which households spend more of their disposable income on energy than on rent. Focusing on universal access to energy for each layer of society, including the poorest, is considered key.

The agenda for urban areas is clear. Form one side, buildings should be energy positive; i.e. be able to produce more energy than they use by exploiting renewable, and by recovering waste energy. From the other side, significant progress needs to be made regarding integrating efficient energy systems, as later debated. Such approaches would fulfil the UN SDG #7, which advocates for reliable, affordable energy services to function smoothly and to develop equitably.

DIGITAL INTEGRATION OF MICROCLIMATES, BUILDINGS ENERGY DEMAND AND ENERGY SYSTEMS

While outdoors microclimates influence the energy demand of buildings, the fabric of the building influences the outdoor microclimate. In the past, common sense and tacit knowledge have led to cities where the spaces surrounding the cities, buildings and outdoor spaces were finely integrated. This contributed to comfortable outdoor and indoor climates achieved with no expenditure of energy. The introduction of mechanical systems and a myopic approach reinforced the idea that any design can be artificially acclimatised, leading to substantial rates of overheating or overcooled public spaces, and to emissions.

Emanuele Naboni aims at establishing a digital design process that leads to comfortable outdoor and indoor microclimates with limited, or no use, of energy. He demonstrates, with the aid of a customised Ladybug Tools (a plugin of Grasshopper) based workflow, that changing the characteristics of buildings, such as the façades, has significant implications on both the outdoor and the indoor comfort.

This leads to the discussion of the thermodynamic coupling of large outdoor areas and multiple buildings in indoor environments. A series of city modelling techniques are thus introduced, which include the analytic modelling of energy consumption of building design alternatives, as well as taking into account a variety of energy systems for energy efficiency. The City Energy Analyst, developed by Jimeno Fonseca, is presented in this chapter. It is a tool capable of performing city-scale energy systems simulation. Combining energy system optimisation to microclimate modelling and building fabric energy demand minimisation is a way of looking into synergies among systems and expertise types that have often remained disjointed.

In conclusion, the contemporary urban planning process demands smart digital workflows supporting informed decisions and facilitating the exchange of information between systems and expertise. The contribution of Theresa Fink stresses the importance of a ‘digital orchestration’ to connect domains by multiple key performance indicators. The presented workflow includes analyses and simulation tools within Rhinoceros 3D, the parametric plug-in Grasshopper, and the environmental plugins included in the Ladybug Tools suite. Combining several analyses aids the achievement of urban regenerative performance and facilitates creative approaches to the adaptation of cities to climate change while enhancing human health and connections to nature.

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OVERVIEW OF OUTDOOR THERMAL COMFORT INDICES

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Since the industrial revolution we have been living in a new geological era, the Anthropocene. Climate change is being enacted, and as such, we should rethink our cities and our lifestyles in order to face it. Summer heat waves are complex and recurrent phenomena which negatively affect the health and wellbeing of the urban population, mostly during the warmer months [1]. In order to face them, it is essential that urban and district planning addresses the pedestrians' thermal perception in order to improve the environmental quality and liveability by designing comfortable and healthy outdoor spaces with improved urban microclimatic conditions. When designing our cities, it is important to understand and optimise the outdoor thermal environment for current and future climatic conditions.

Several strategies exist to improve the thermal quality of cities: i) the use of cool materials, which are characterized by a high solar reflectance and high infrared emittance [2], [3]; ii) the design of reflective surfaces and cool pavements, which are able to decrease the surface and air temperatures [3], [4]; iii) green roofs [5] and vertical greening systems [6]. Sound urban planning should also improve the natural ventilation in the built environment as well as the daylight availability, both indoor and outdoor [7]. Smart landscape design (e.g. parks, grass, trees, green roofs and vertical greening) offer great potential to decrease negative impacts of extreme weather conditions [8] and improve the outdoor thermal comfort [9] by moderating the ambient temperature through shading and the evapotranspiration process [10], [11]. Finally, the thermal properties of the ground covering and their albedo play a major role in the outdoor thermal comfort [12], [13].

MODELLING OUTDOOR THERMAL COMFORT

In order to improve the outdoor urban thermal conditions, it is important to compute, precisely and methodologically, the pedestrians' thermal comfort. People tend to adapt themselves (physically, physiologically and psychologically) in order to be comfortable with the thermal environment, and human comfort has been quantified in several models, which are subdivided into three main categories: i) thermal indices, ii) empirical indices, and iii) indices based on linear equations. The first group of models, so-called thermal indices, are based on the human's energy balance, representing the physiological exchanges between the body and the thermal environment. The second group, so-called empirical indices, consist of models expressed as linear regressions and are based on field studies (e.g. monitoring and surveys). These models are quite simple to use and perfectly fit the climatic conditions where they were developed. Finally, the indices based on linear equations predict human comfort as a function of two or three environmental parameters (e.g. air temperature, wind speed and humidity) [14].

SIMULATION FOR CLIMATE, URBAN ENVIRONMENT AND PEDESTRIAN

When approaching thermal comfort modelling, it is important to correctly select the suitable comfort model by addressing the following three points: i) the climatic conditions, ii) the urban environment, and iii) the physical characteristics of the pedestrians. Regarding the climate, each model was designed, validated and applied for certain meteorological conditions. Consequently, the models have different thermal scales from each other, as well as different sensitivity to weather conditions. Only three comfort models cover all thermal sensations, measured on an 11-point scale, from extreme heat stress to extreme cold stress: i) Universal Thermal Climate Index (UTCI), ii) Perceived Temperature (PT) and iii) Man ENvironmental heat EXchange model (MENEX). It is consequently quite important to carefully read all previous studies performed with each thermal index before selecting the most suitable one. The second point to address when selecting a model is the impact of the built environment, as each model has its own level of sensitivity to the physical properties of the space (albedo, thermal properties etc.). As an example, only COMFA*, ETU (Universal Effective Temperature), ITS (Index of Thermal Stress), PET (Physiological Equivalent Temperature), PT (Perceived Temperature), UTCI and PMV (Predicted Mean Vote) properly quantify the microclimatic conditions of the site (e.g. radiative environment, albedo of the surfaces etc.).

These parameters are essential in order to understand the impact of materials (e.g. asphalt, concrete etc.), greening (tree and grass), and also the mutual relationship between buildings. The third and final point to address is related to the physical properties of the pedestrians, such as their metabolic activity or clothing's characteristics.

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CLIMATE WALKS TO EVALUATE OUTDOOR COMFORT

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Microclimate in the built environment is known as a local phenomenon that affects the well-being of people and can also be an index for urban liveability. It was proven that outdoor comfort conditions in cities and public spaces are a driver for how frequently people use and occupy public spaces [1]. Public spaces with optimum comfort levels enhance the quality of cities by encouraging cycling and walking, attracting a higher number of people to public spaces and providing opportunities for business and tourism, which can promote the economic sustainability of cities [2],[3]. Microclimate studies are one of the domains where physical, spatial and temporal fields merge to define design concepts that address climate change, resource availability, environmental degradation and energy consumption issues [4]. The complexity of urban contexts demands advanced techniques and methodologies. Microclimate studies are often performed with the aid of computational modelling, digital tools and simulation techniques [5].

However, the human dimension is generally underestimated in such studies. To bridge this gap, a methodology named *'Climatewalks'* was developed at TU Munich. This is a Human-Cantered approach to understand local microclimate at a pedestrian level as a way to facilitate design interventions to increase comfort levels and to prefigure how to mitigate extreme climatic conditions. From this perspective, Climatewalks focus on humans as a source of information that is captured by methods including measurements, simulations, and data mining [6],[7].

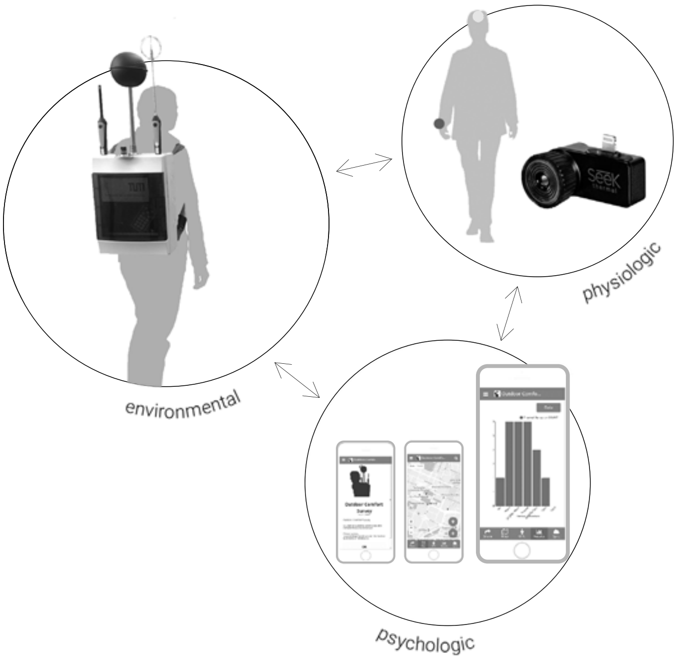
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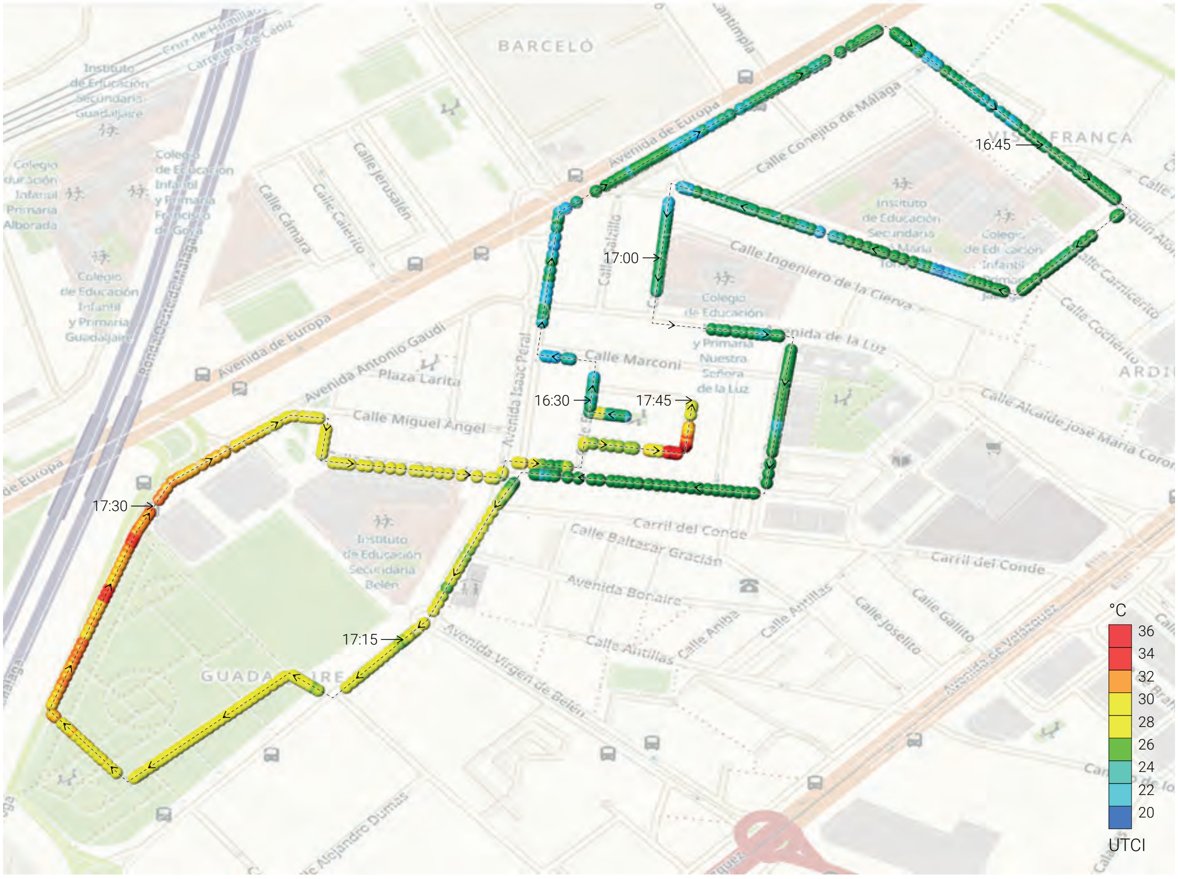
Figure 4
Mobile micro-meteorological sensors collecting data in Malaga, Photo by Loredana Bruma

CLIMATEWALKS IN MALAGA

During a workshop in Malaga in Autumn 2018, students gathered measurements by mobile micro-meteorological sensors (Figure 4) that were selected for the measuring of relevant environmental parameters to investigate thermal comfort, including wind speed, air temperature, humidity, globe temperature and solar radiation to calculate the universal thermal climate index (UTCI) [8]. A thermal comfort questionnaire within a designed app was also used for collecting data about subjective perceptions and thermal sensations. A measurement backpack was carried while walking through outdoor spaces to collect data for all of the selected routes. The routes were pre-selected so that the measurements could be completed within 90 minutes. Another factor was the skin temperature of people, which was measured with an infrared thermal camera, which was adapted to the cell phone's camera (Figure 5).

Data visualization done by using Rhinoceros, Grasshopper and the plugin of Ladybug Tools, allowed for importing maps for each route, and a series of scripts in Python code were developed in order to combine data from CSV (Comma Separated Values) files. Overlaying all collected data (wind speed, relative humidity, air temperature, global temperature and UTCI) with the actual routes on a two-dimensional plane (2d) ,as in Figure 6, which shows the path.

Figure 5
The framework of the Climate Walks method to monitor environmental, psychological and physiological parameters with the aid of a georeferenced system.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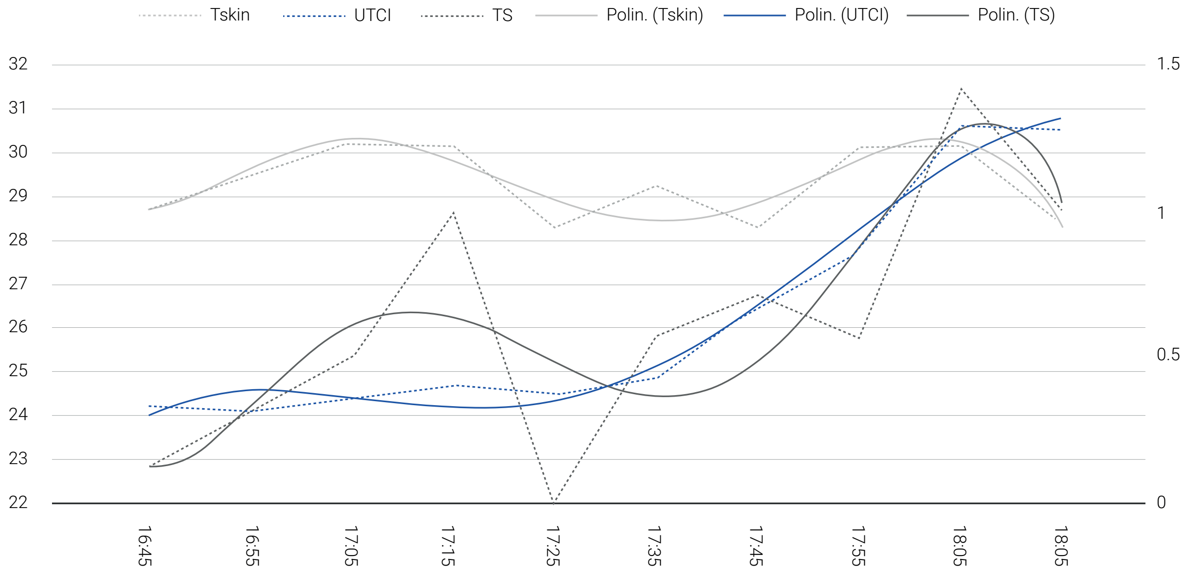
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Figure 6

An example of a Climate Walk performed in Malaga. UTCI map indicating every 15 minutes over the walking route. The variable UTCI shows how to open areas are more exposed to direct solar radiation, while shaded densified areas are protected, thus positively influencing the UTCI. Green areas offer comfort when compared to the densified areas, where cars and concrete characterise the landscape

In order to investigate the temporal and spatial effects of outdoor comfort on people, the data is segmented into 15 minutes intervals as shown in Figure 6. The results show a continuous increase of UTCI over the walk due to increase in solar radiation (changing from the overcast sky to sunny) and by shifting from densified and shaded areas to open areas where solar radiation is not filtered. This increasing trend from 23 °C to 31 °C within 1.5 hours corresponds to the thermal sensation votes measured by the apps, which moved from Neutral to Warm sensation for the subjects. This trend also validates the UTCI results, in which a temperature above 26 °C is categorized as 'moderate heat stress' as shown in Figure 6.

The skin temperatures values (Tskin) in Figure 7 follow an increasing trend within the first 15 minutes of the experiment up to 30 degrees, but they drop later for the next 30 minutes. This trend ascends with the increase of UTCI relatively. Choi and Loftness [9] argued that skin temperature is a suitable indicator of an individual's thermal sensation in a thermally uniform environment. However, in this study, temperature of the forehead was recorded at each point of the walking route, but this measurement may not be representative of human physiological response to the thermal environment.

As a summary, the Climatewalks experiment setup for outdoor comfort studies has the potential to find answers to the challenges of thermal comfort perception in more complex outdoor environments and to formulate indications for designers, city planners and policy makers in high resolution and on a micro scale.

Figure 7

Graphical correlation of UTCI, skin temperature (Tskin) and thermal sensation (TS). The continuous polylines average the point in time values to offer more clarity of interpretation of patterns

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REGENERATIVE NATURE-BASED SOLUTIONS AND TECHNOLOGIES

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Landscape architecture has experienced a paradigm shift in the last two decades, requiring designers to respond with evidence-based design to the dynamic and temporal quality erosion of the urban ecosystem. The Green Infrastructure (GI) approach promotes the elements of biodiversity and organised systems that are part of natural capital in an urban area, be it valuable or derelict, including individual technological devices that leverage biodiversity and are integrated into the architecture. Green roofs and living walls, permeable pavements, rain gardens and other systems for the collection and management of rainwater are just some examples. By providing ecosystem services, GI promotes environmental protection, economic feasibility, health and well-being, and equality and social inclusion. In particular, salutogenic design value creation has become central, introducing in architecture and urban design a focus on metrics alongside form and aesthetics.

THE AVASARA ACADEMY

The Avasara Academy (Case Design, Transsolar Klimaengineering, Hemali Samant landscape architect, 2016) is a residential school campus in Lavale, a rural village located 145 km Southeast of Mumbai, India. The Academy comprises seven buildings with classrooms on levels one and two, and student dormitories and faculty residences on levels three and four. As a key result, this project has achieved indoor thermal comfort without mechanical systems in a hot and humid country, such as India. The passive-adaptive strategies implemented by the designers encompass: strategic program placement, climate responsive massing, locally sourced wooden shades, screened and shaded outdoor living areas, and a purposely-designed natural airflow which benefits all functional spaces, contributing to a year-round comfortable learning and living environment (see Figures 8 – 11 and chapter cover). Outside air, passively pre-cooled, is drawn through a series of earth ducts, and then supplied to the indoor spaces. Chimneys are designed to passively drive the entire airflow and provide cooling. The same strategy also contributes to the elimination of outside noise transmission into the classrooms.

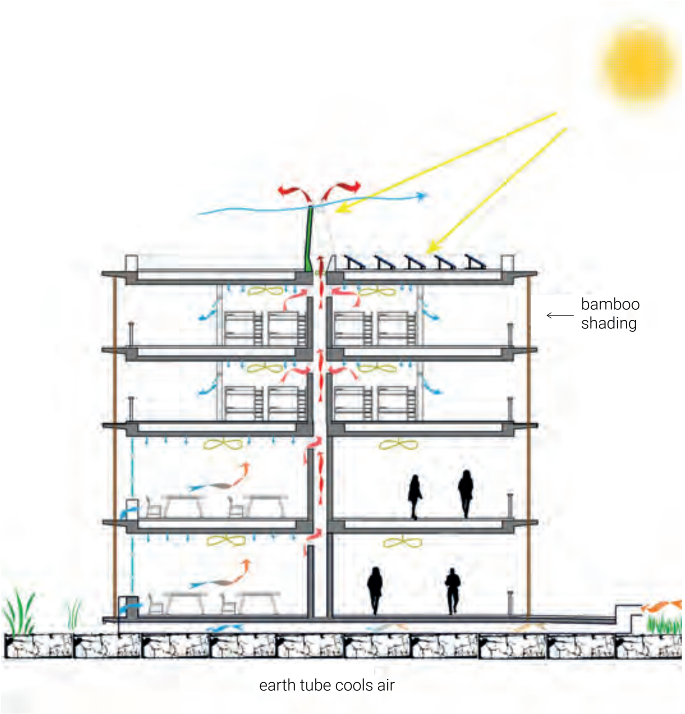

Figure 8
Solar chimney drove natural ventilation – Fresh air is cooled down through earth ducts before it enters the habitable spaces and is exhausted through a dedicated ventilation shaft connected to the solar chimney. Copyright Transsolar

Concrete and locally sourced stone provide necessary thermal mass in functional spaces, resulting in a moderate and more consistent radiant temperature inside the buildings. Solar water heaters provide hot water and PV panels supply electricity, making the Academy also a Net-zero Energy Building.

RESISTANCES TO DIGITALLY MAPPING LANDSCAPES PERFORMANCES

The beauty and intrinsic value of nature are inspirational for most, but it seems that talking more about its functional qualities may, for now, prove to be the most persuasive way to bring the benefits of green infrastructure into sharper focus. Recent feedback [6] suggests that different digital tools (ENVI-met, CitySym, Ladybug Tools) have great potential to describe the microclimatic conditions of the built environment, the interactions with its natural capital, and the related impacts on human comfort.

Despite successful histories of early adoption in automated mapping technology, spatial analysis and Geographical Information Systems, landscape architecture demonstrates a widespread resistance to computational techniques, which has until recently limited practitioners' ability to explore 'landscape performance' as part of design processes. Digital techniques can help designers to explore the ideas and concerns core to landscape architecture in the Anthropocene, such as designing with social-ecological systems, working with landscapes in flux, or adapting to the extreme weather events caused by climate change. Processes of feedback, sensing the environment, managing the identified data, and visualizing climate adaptive responses represent the core design focus in the development of inclusive urban landscapes and resilient communities.

Some of the aspects contributing to difficulties in theoretically and culturally conceptualising a role for digital technologies within landscape design processes include: the belief that technology negatively influences creativity, with landscape design conceived as requiring just individual creativity and human spontaneity; the limited understanding of the potential of digital technology, reducing its value to that of a 'virtual drawing board' to replicate analogue models of representations; the manner in which design projects are discussed, with emphasis on the representational quality of the image and not on the role of digital technologies in the generative design process - i.e. disciplinary tendencies to over-emphasise the conceptual and representational aspects of design over design processes and construction details [1].

Figure 9

Avasara Academy – Entry courtyard. Transsolar, Case Design, and landscape architect Hemali Samant implemented integrated clima-design and nature-based solutions for the Avasary Academy, thus creating a year-round comfortable learning and living environment. Copyright Ariel Huber, Courtesy of Case Design

Figure 10
Avasara Academy – Bamboo façade detail. Copyright Ariel Huber, Courtesy of Case Design.

FOCUS ON MICROCLIMATES

As cities expand and urban populations soar, competition for space from various land uses has become more intense, resulting in green space and nature being squeezed out of many cities and marginalised from urban decision-making processes. High urban land prices have made it harder to justify urban greening, which has become undervalued and long regarded as an aesthetic nicety, rather than a fundamental component of the urban fabric. This situation is hugely detrimental for many city inhabitants, and their environments, as well as the economic well-being and robustness of urban areas to the effects of climate change [2].

Due to its impact on the quality of life of urbanites, a particularly critical factor affecting urban ecosystem resilience is microclimate. Dense urban geometries and lack of permeability of the site's surfaces generally determine thermal discomfort and the presence of Urban Heat Island effects, with various degrees of intensity depending on the time of day and the seasons.

Studies on microclimates of cities have already proved that human comfort, health and well-being are strongly influenced not only by the geometry and the level of soil sealing but also, and predominantly, by the presence of natural elements and systems and their integration within the built environment [3]. The lack of green open space impacts, in particular during the summer, the radiative properties of the environment and has negative effects on the urban microclimate, and potentially very harmful consequences for the population and the entire ecosystem. The need to assess vulnerability and adapt to critical environmental phenomena consequently calls for new ways to understand, interpret, experience, and interact with - from the early stages of the design process - all the components of the urban ecosystem.

LANDSCAPE PERFORMANCE

Landscape performance can be defined as a measure of the effectiveness with which nature-based solutions fulfil their intended purpose and contribute at different scales to sustainability and resilience through the provision of ecosystem services such as local climate control, air quality regulation, water purification, soil and water retention, recreation and aesthetic values, cost savings and other economic benefits. The meanings of performance in landscape architecture are indeed multiple and intertwined and are irreducible to simple, succinct definitions [4].

The growing body of global research now available on nature and green spaces tells visionary stories. It ably demonstrates the critical importance of green infrastructure within urban environments and the intrinsic relationship that humans as a species have with it. It demonstrates the multifunctional benefits it delivers at all scales, which are crucial to enable humans to flourish in urban environments, and the role it can play in supporting the economic, social and environmental health of city environments.

Figure 11

Avasara Academy – Outdoor activities
Copyright Ariel Huber, Courtesy of Case Design.

More and more advocates of a digital landscape design practice – Arup, Transsolar, Case Design, Turenscape, Ramboll, and West 8, to cite just a few – are disseminating methods and tools for quantitative performance-based projects, with key performance indicators offering a comprehensive and innovative approach to the design of the urban built environment, and progressing the implementation of digital tools in landscape architecture. Combining this shift with the increased attention to nature-based technologies and increased accessibility to digital tools supports a new approach for challenging static design solutions [5].

Developments like the Olympic Park (Arup, London), the Avasara Academy (Transsolar, Case Design and Hemali Samant landscape architect, Lavale, India), Bishan-Ang Mo Kio Park (Ramboll, Singapore), Madrid Rio (West 8, Madrid, Spain), and Quzhou Luming Park (Turenscape, Quzhou City, China) represent successful attempts to rationalize interactive architecture and responsive technologies through the lens of contemporary landscape architecture. These examples shows that in the near future, landscape performance will increasingly underlie debates about restorative architecture, green infrastructure and nature-based solutions, thereby allowing it to play an important communicative and collaborative role in climate change policy and in practice, which will lead to improving people's quality of life - making them healthier, happier and more productive.

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GREEN AND BLUE INFRASTRUCTURE FOR OUTDOOR COMFORT

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Caused by natural and human activities, climate change amplifies social conflicts resulting in a precarious welfare state, lack of access to public services and an ever-growing economic inequality among people. From this point of view, the city of Rome appears as a city of conflicts of different nature. Despite the high percentage of green areas within the city boundaries (71% of the municipal area is covered by the Ager Romanus), the ecosystem services are threatened continuously by uncontrolled urban sprawl phenomena. Extreme events - mainly related to climate change, human activities and soil sealing - impact on thousands of vulnerable people and affect their quality of life. A recent study, based on the indexes of social distress and disadvantage, shows that the districts with the highest social and environmental distress are located in the areas around the urban ring-road where the public transport is inefficient and isolation still produces significative negative impacts in terms of environmental costs and quality of life. Districts like Vigne Nuove, which is the focus of the study, represent in Rome the international Modernist movement logic of the self-sufficient neighbourhood, built by 'Existenz minimum' principles [1] and with low-cost construction technologies.

Vigne Nuove district was drawn up in 1973 by a group of designers coordinated by Lucio Passarelli. This housing complex, despite the environmental and social degradation, retains the qualities of a theoretical-experimental architecture [1]. The outdoor space, located on the ground level, is characterised by the massive presence of concrete and asphalt, which considerably increase air temperature and affect human thermal comfort, air quality and energy use of buildings. This study explores the potential of a green-blue infrastructure approach to mitigate the impact of heat waves on the outdoor spaces and to increase social connectivity and equity among the residents. In the context of an urbanised environment, green and blue infrastructure is to be understood as all natural and semi-natural landscape elements that (could) form a green-blue network. It can refer to landscape elements on various spatial scale levels: from individual rows of trees to complete valley systems.

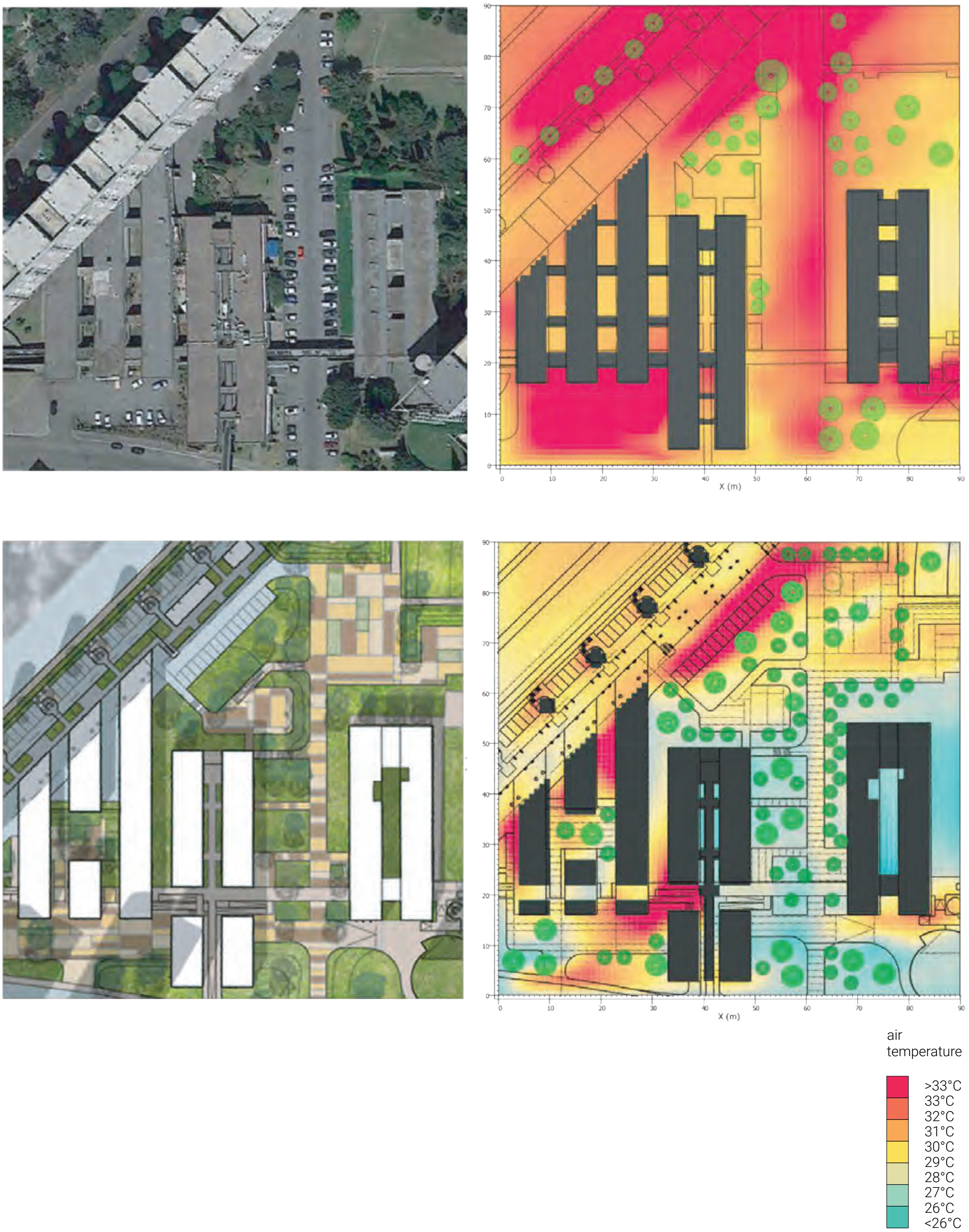

Figure 12

Comparison of the air-temperature analysis between the existing condition (top) and the new proposal configuration (bottom).

Examples of green landscape elements are hedgerows, copses, bushes, orchards, woodlands, natural grasslands and ecological parks. Blue landscape elements are linked to water. They can be pools, ponds and pond systems, wadis, artificial buffer basins or watercourses. Together they form the green-blue infrastructure [2].

GREEN-BLUE INFRASTRUCTURE

A green-blue Infrastructure is here designed to generate biodiversity and increase ecological and social connectivity and includes environmental justice, equity, health, and physical and psychological well-being. From a social point of view, requalification of the outdoor space concerns the re-functioning of the parking area through the creation of a new public human-scaled space for social activities and interactions, which is in line with the Living Building Challenge Equity petal [3]. The intent of the Equity Petal is to transform developments to foster a true, inclusive sense of community that is just and equitable regardless of an individual's background, age, class, race or gender.

Microclimate analyses of the proposed design were performed using ENVI-met [4],[5] to simulate the surface-plant-air interactions and the distribution of relative humidity, air temperature, ventilatory flows (including turbulence phenomena) and mean radiant temperature. In the new proposed open space configuration, the air temperature drops from 33-35°C in the existing conditions to 26-28°C (Figure 12). The outcomes represent a valid application of a scientific approach towards the production of easily understandable data that can support and drive both the public decision-making process and the definition of greening design strategies.

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CO-MODELLING WATER AND MICROCLIMATE

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The world is becoming more and more urbanised: in 2014, 73% of the population of Europe lived in cities and 54% of the world's population did the same, and in 2050 that number is projected to be 66% [1]. Cities are places where people live, work, meet, trade, play and in general interact with each other. These interactions either require an outdoor space or transport through such a space.

One of the most important factors for human activities within the city is if the weather is good or not. The weather can be subdivided into three climate levels: macroclimate, local climate and urban microclimate. Macroclimate is the surrounding climate related to the location; the local climate is the climate surrounding cities, and the urban microclimate is climate experienced in streets, squares and parks in the city [2]. The microclimate of a particular area is determined by the geography and location of that area. The local and microclimate are influenced by the macroclimate but are also highly dependent on the fabric and geometry of the city [3]. The Urban Heat Island (UHI) is a well-known and documented example of interdependencies across scales. [4]. The phenomenon describes the local increase in temperature within a city compared to the rural surroundings. The increase in temperature is, among other factors, caused by the difference in surface coverings between urban and rural locations and especially by the lack of vegetation in the urban context.

Even though the UHI effect is a local climate phenomenon caused by and influencing the city as a whole, it is made up of the different microclimates in the city. While it is difficult and complex to make citywide changes to alter the local climate, the microclimate can be influenced more easily. Vegetation, canopies, building shapes and street geometry could be formed, so they provide the right amount of shade from the sun, blockage from the wind and control of relative humidity in order to minimize UHI or, in general terms, in order to provide comfortable outdoor spaces.

Figure 13
Taasinge Plads, Copenhagen, Denmark (Courtesy GHB Landskabsarkitekter / Steven Achiam)

Figure 14
Taasinge Plads, Copenhagen, Denmark (Courtesy GHB Landskabsarkitekter / Steven Achiam)

Much research has been undertaken to describe the effects of surface coverings and geometries on microclimates, but the vegetation aspect has often been neglected. Plants and trees also contribute to the thermal comfort of outdoor spaces. They block the wind, thereby creating shelter, and furthermore, trees create shade from direct sunlight. These effects are well described and can be computed in practice. However, the effects of evapotranspiration of plants and trees on the microclimate are not well described within the building engineering disciplines.

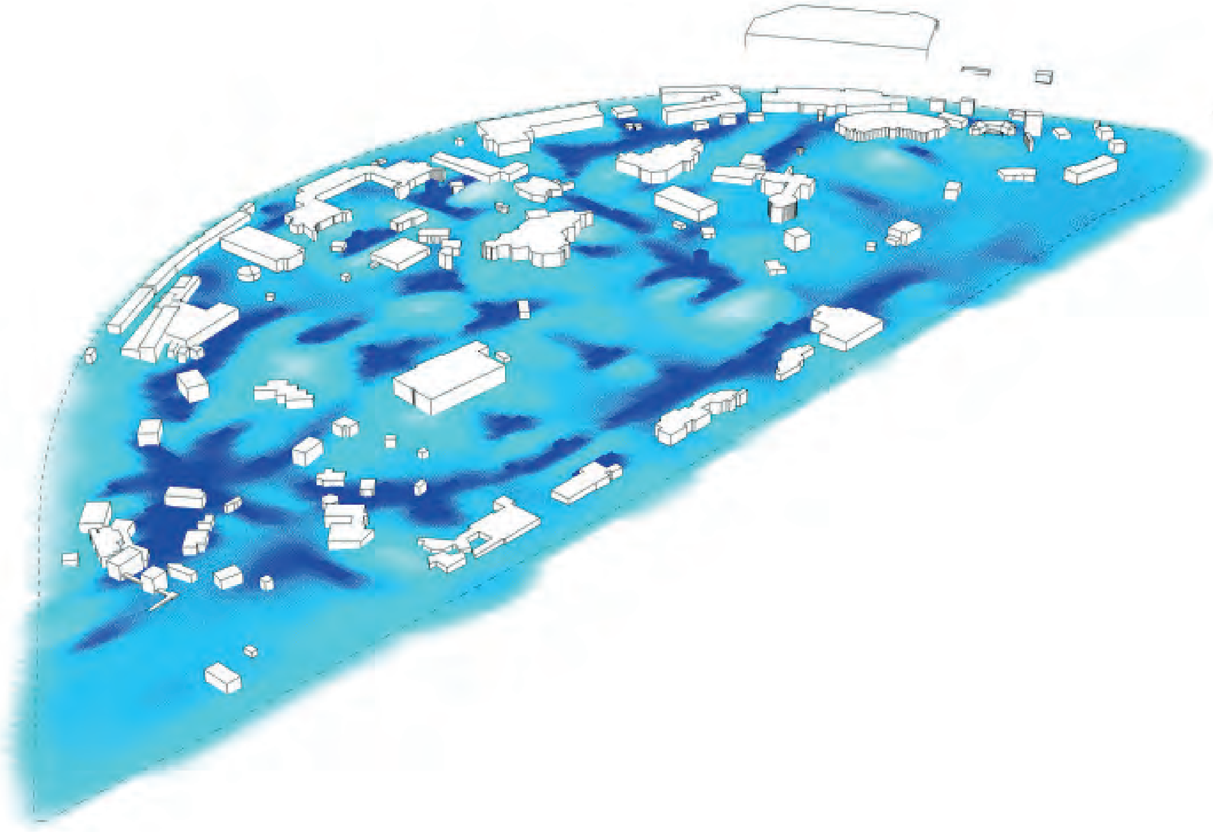
Figure 15
Stormwater run-off analysis conducted for Philadelphia Zoo (Courtesy Bjarke Ingels Group)

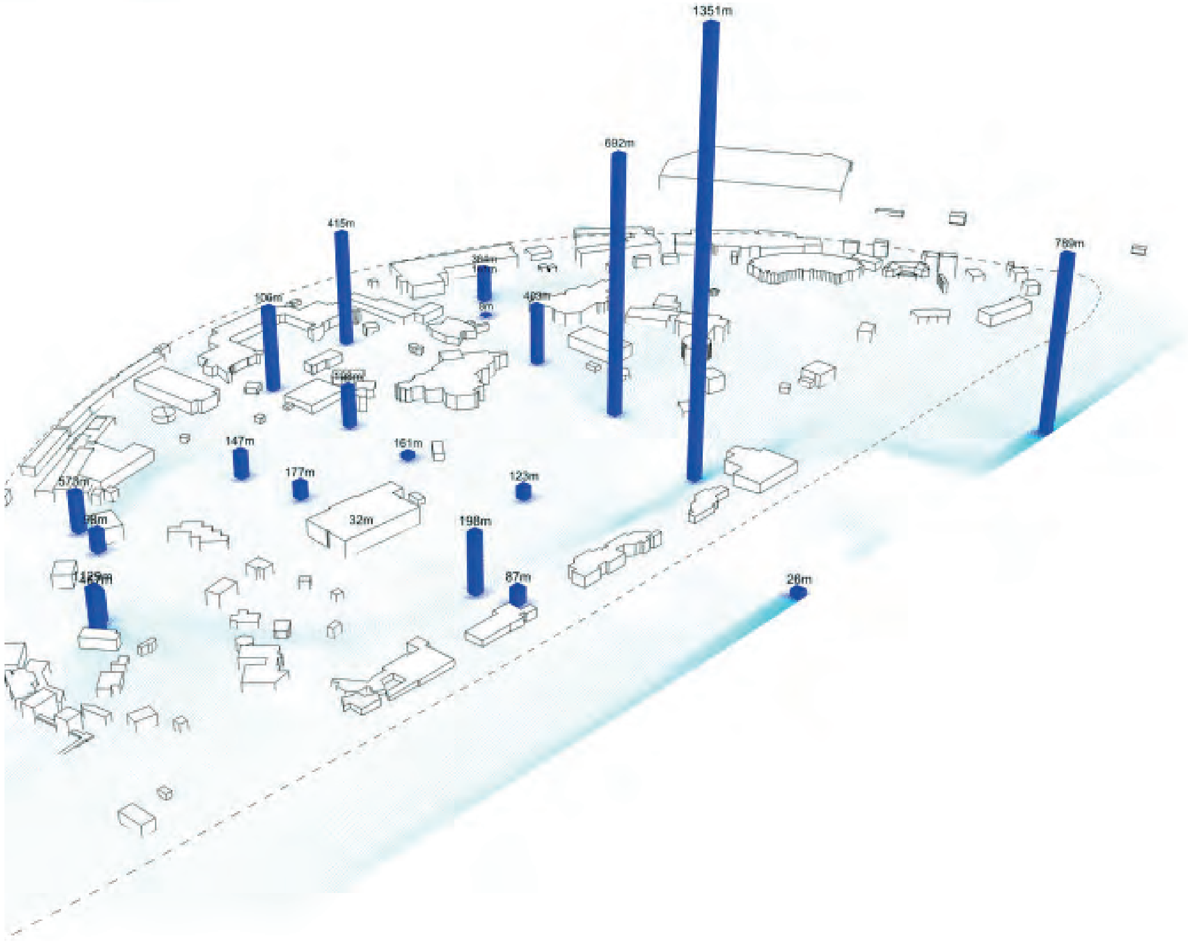
THE LIVESTOCK PLUGIN

Livestock is a software plugin created to make up for the lack of knowledge of the effect of vegetation in the built environment and was first introduced in [5]. Livestock is a package for Grasshopper providing components for modelling water movement and hydrothermal effects around buildings to enable and evaluate sustainable solutions in which those effects are incorporated. Livestock and its hydrological simulation engine can compute the evapotranspiration of plants and thereby enhance the current methodology of outdoor comfort evaluation.

By creating a good outdoor space, it is meant to control several factors such as stormwater management, and better outdoor microclimate can be acquired. Even though these seem unrelated, they are connected and can be used to influence each other. The nature of the hydrological engine within Livestock makes it possible to evaluate both stormwater management and evapotranspiration. Situations such as the 2011 Copenhagen stormwater event, which caused parts of the northern part of the city to become flooded, show that there is an urgent need to tackle these problems.

A recent example of coupling between stormwater management and recreational space is the Taasinge Plads project in Copenhagen conducted by GHB Landskabsarkitekter (see Figure 13 and Figure 14). They introduced vegetation to a square in the neighbourhood of Østerbro. The green areas both function as recreational spaces and as stormwater basins, which would prevent flooding of the buildings around the square. While it might not have been the top priority of the design team, they also influenced the thermal comfort of the square by changing the urban fabric and increasing the evapotranspiration of the area.

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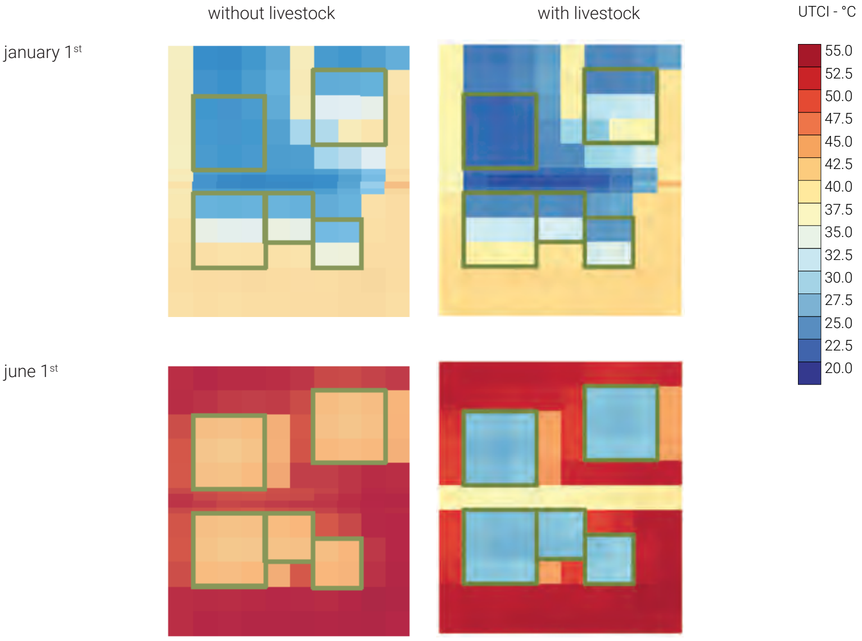

Figure 16
Effect of evapotranspiration on UTCI in Abu Dhabi (Source: [5])

The run-off capabilities of Livestock were used to calculate a stormwater event at the zoo in Philadelphia, USA (Figure 15). The analysis was done as part of a larger assessment of sustainable design options for the Zoo. The main prospect is to collect rain water, redistributing it, cleaning and using it for multiple usages, such as animal sea- and freshwater tanks, park toilets, watering plants and more. The runoff analysis was used to estimate the volume of water to expect and where to collect the water for all these purposes. Another use of the analysis was the resilience aspects and how to design hard surfaces to withstand extreme flood events and storm water prevention that may harm the park wild life. The analysis helped take action on the entire landscaping as well as the more technical sewage distribution system.

Livestock was also used to evaluate the benefit of trees and a water stream in a new neighbourhood in Abu Dhabi [5]. Abu Dhabi is located in a hot and dry climate, and throughout most of the year the air temperature is above 20°C, and it is not unusual to have temperatures above 40°C. These temperatures make it an ideal location for the use of evaporative cooling. The analysis was centred around a small area on both sides of a wadi. The investigation compared the UTCI in a situation where evapotranspiration from the trees and the water in the wadi were neglected and one where Livestock was used to calculate the evapotranspiration of the trees and water. The charts (Figure 16) show a clear benefit of the evapotranspiration on the UTCI. Under the trees during the summer, there is almost a 15°C difference in UTCI between computing with and without evapotranspiration.

The water vapour is assumed stationary in the current implementation of Livestock, meaning it will not mix with the air outside of the mesh face where it was created. In reality, this is of course not correct as water vapour would be dispersed by and mix with the wind/airflow. The current state of Livestock is the first step towards computing the influence of water and the influence of water vapour on the microclimate. The case studies show the usefulness of Livestock in the design phase, where it can be used to make more informed design decisions and designs with greater biophilic integration.

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DESIGNING TEMPERATE AND POLLUTION-FREE ENVIRONMENTS

Jakob Strømann-Andersen *Henning Larsen, Denmark*

Since we spend 90 per cent of our daily lives indoors, designers must make our indoor environments as comfortable as possible. Our approach to design must address the reality of an indoor-dominant modern lifestyle but must also proactively work to make outdoor public spaces as comfortable and accessible as possible. It is critical that we provide liveable, well-ventilated and healthful spaces, and foster a close relationship between interior spaces and outdoor access. At Henning Larsen, the aim is to draw on contemporary research and broad knowledge bases to create design parameters that encourage these healthful interiors. Urban microclimates are defined by a local set of atmospheric conditions -- wind, sun, humidity, -- that have a significant influence on the concentration of air pollutants, thermodynamics and air quality. Here, we explore some of the core concepts that maximise our regular exposure to the natural world, both in bringing nature into our interior spaces and by reframing outdoor areas as cities' active social spaces. These concepts are illustrated using their application in a real-life case study, the Etobicoke Civic Center in Toronto, Canada (see Figure 17-21). By means of microclimatic analyses, the outdoor season of the squares and courtyards accompanying the building has been extended by five weeks.

EXTENDING THE OUTDOOR SEASON BY DESIGN

One of the most common barriers to greater outdoor engagement is an inhospitable local climate. Outdoor recreation is an unappealing option for well over half the year, owing to severe cold, heat, precipitation, darkness or other factors. However, architects and urban planners have a unique opportunity to extend the outdoor season by integrating urban physics and climate knowledge into urban planning. Deliberate building massing, landscape design and shading strategies can help reclaim the outdoors for the public realm by creating more comfortable microclimates, shielding building users from the environmental factors that might drive them indoors.

Figure 17

Through careful analysis of the relationship between building volumes and local climatic conditions, Etobicoke Civic Center extends the comfortable outdoor season in outdoor plazas, giving more life to the public realm (Courtesy Henning Larsen)

Understand the climate and context. When designing cities, neighbourhoods, and buildings, it is essential to understand the local climatic context. Since the microclimate is shaped by the interaction between the climate and the built environment, the first step of any urban design scheme should be to understand the macroscale climate conditions and seasonal weather patterns. In a practical sense, this means that the design phase must be preceded with extensive research on local climatic patterns so that the ambient outdoor conditions can inform architecture from the first sketch (see Figure 18).

Create outdoor comfort strategies. Determine what is important. For instance, in cold climates, perceived temperatures should be increased, and in warmer environments, minimised. In general, there are six climatic parameters influencing the human heat balance, and thereby our perceived thermal comfort: air temperature, diffuse radiation, direct radiation, infrared radiation, relative humidity and wind speed. By collecting local statistics on these parameters, it is possible to see which parameters play the largest roles in determining perceived outdoor comfort in the local context.

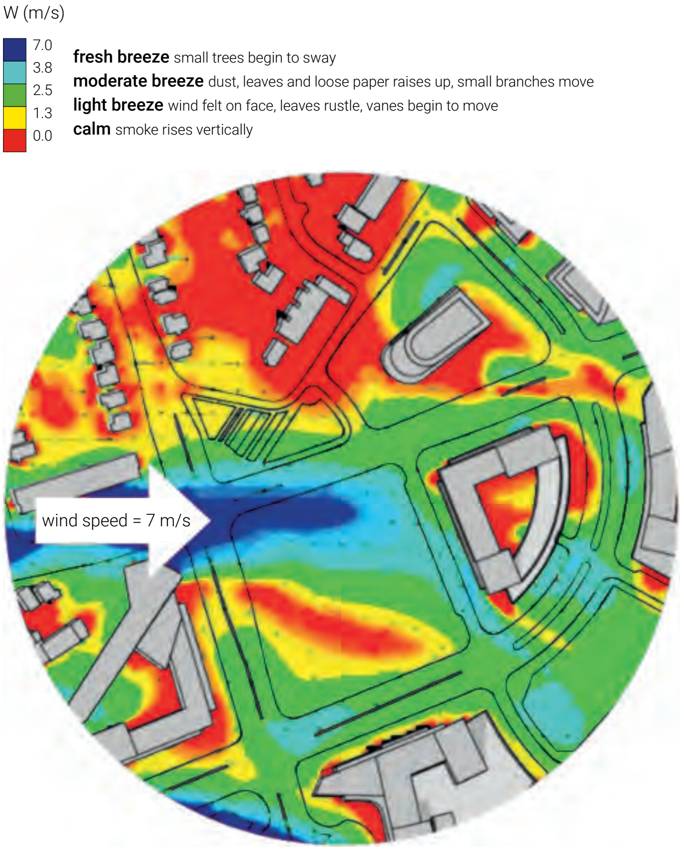


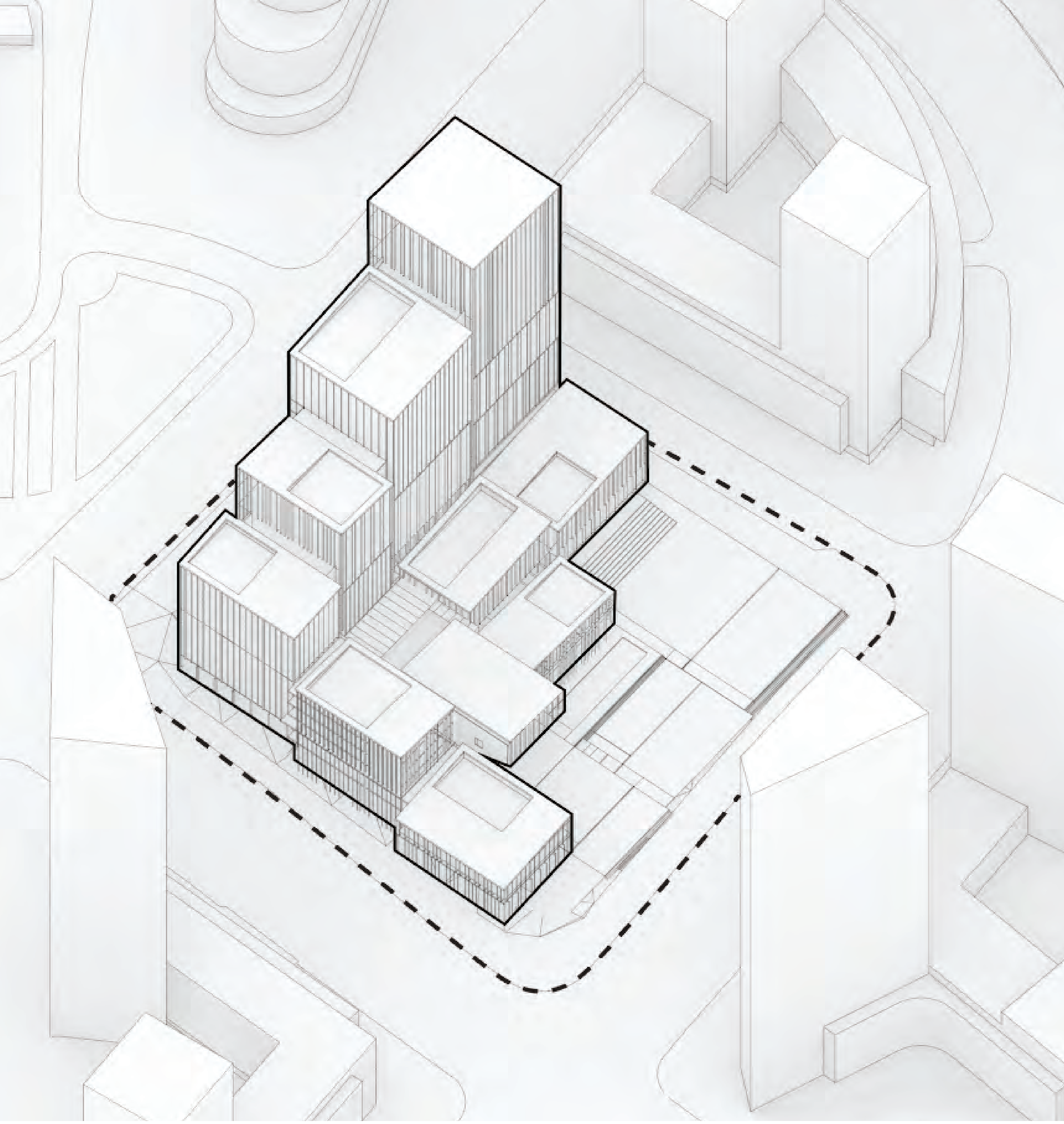
Figure 18

Results of a initial local wind study for Etobicoke Civic Center project in Toronto, Canada. In Toronto, the summers are comfortable; the winters are freezing, dry, and windy; and it is partly cloudy year-round. Over the year, the temperature typically varies from 17°F to 78°F and is rarely below 1°F or above 85°F (Courtesy Henning Larsen)

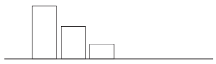
Implement strategies in the masterplan concept. Transform the visions for the microclimate into design guidelines for the larger project (see for example, Figure 19 and 20). This is particularly relevant in the strategic sculpting of building geometries: The way that building volumes and orientations relate to one another is a critical factor in determining the climatic effects on a project's surroundings. The composition and shape of the building have a considerable impact on the wind flow and sunlight exposure in the public realm, and these factors are essential for our outdoor comfort. Remember that this is a task of compromise, of graceful balance with other project priorities. At a waterfront, the architectural vision for us will always be to open it up, although this strategy might not be the best solution regarding wind-chill effects. As such, we need to look to other microclimate-influencing factors to achieve both social, practical, and microclimatic priorities. The local climate could be shaped with other factors, like reducing building heights (to minimise severe wind flow on the buildings' leeward facades) and strategically placing vegetation to support the microclimate strategy.

Figure 19

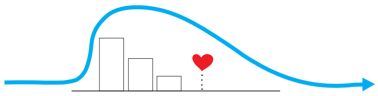
At this site in Toronto, the construction of the building has been designed to block out cold wind flows and push them upwards along the building. The wind is directed according to the orientation of the towers and the way they gradually rise upwards. This ensures shelter from the wind in the open square, as well as on the various rooftop terraces (Courtesy Henning Larsen)



initial situation



our design



solution to the problem

Optimise and validate with simulations. Energy modelling technology is a critical component in guaranteeing a successful microclimate strategy. It enables design teams to test out different scenarios during the design process, optimising all contributing factors for the final design. Shadow movement measurements, sunlight pattern studies, CFD-wind simulations and even heat-map visualisations on the perceived temperature (by applying the Universal Thermal Climate Index) can quantify the impact of the strategies. Measure twice, cut once, as they say – Better preceding research leads to a better-performing final product.

Program the outdoor functions according to the microclimatic conditions. Once you have created the conditions for a great outdoor realm, it is important to program the urban spaces to accommodate it. Place the café in the sun, orient the facade of the bakery towards the east to expose it to the morning sun, place the dumpsters in the shadow and the playground in the sheltered, wind-free spot. This will foster a better public life all year round. Building volumes will interact with the climate and influence the microclimatic parameters of the surrounding area, and thus the outdoor comfort. By doing so, it might be possible to enjoy the first spring dinner outside in April rather than in May.

CLEAN AIR BY DESIGN

Researched design for urban microclimates frames comfort in atmospheric terms. However, to establish outdoor spaces as appealing social destinations, and to increase well-being in interior spaces, we need to consider the quality of the air itself. Avoiding overheating, excessive solar glare and disturbing wind factors are only part of the equation. As cities around the world struggle with harmful air quality, the importance of this in urban design becomes ever more critical. Fresh, clean air improves our mood, boosts our productivity and ultimately supports our physical well-being. Architects, urban planners and designers have a responsibility to consider the importance of clean air from the very beginning of the design phase, allowing its prioritisation to shape their ultimate vision. Here are a few fundamental concepts toward realising this practice.

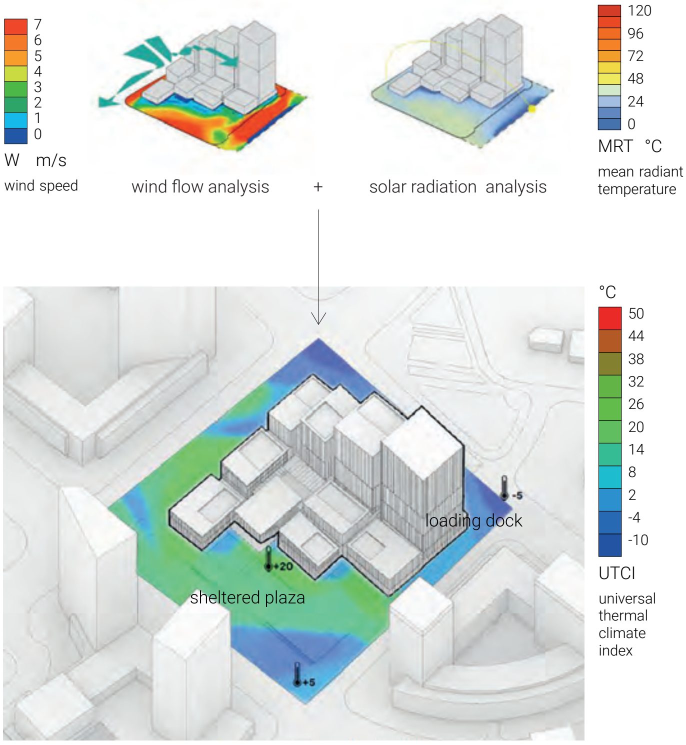


Figure 20

The scenario visualised here projects a sunny spring day in Toronto with an outside air temperature of 3.9° Celsius (Ta), a mean radiation temperature of 40° Kelvin (Tmrt), and relative humidity of 78% (RH). How does the wind affect the thermal comfort in this case? In a windless environment (0.1 m/s), we can see the UTCI physiological temperature is equivalent to 20.0° Celsius, but in a windy environment (10.0 m/s), it would be equivalent to -6.0° Celsius (Courtesy Henning Larsen)

Let urban ventilation do the work. Wind flows, temperature gradients, solar radiation and humidity levels influence pollutant concentrations and dispersion. The way air moves between building volumes determines the level of urban ventilation, as breezes transport pollutants by advection and can transport airborne pollutants into previously undisturbed pockets of clean air. In general, low wind speeds create a more favourable environment for the chemical reactions necessary to generate ozone and particle pollutions, which is why wind-sheltered areas can end up concentrating pollutants. Therefore, it is necessary to balance beneficial ventilation while avoiding harsh wind flow – In public squares as well as homes and offices, we must allow our cities to breathe.

Consider building heights. The difference in building heights, especially in more concentrated masterplans, influences the mixing of pollutants with clean air. Studies addressing pollutant dispersion concerning large-scale building massing suggests that a city's street grid is oriented to the prevailing wind directions, which becomes a major influence over smaller-scale ventilation efforts. As an example, consecutive blocks of tall buildings form sort of an urban canyon – As can be observed in New York, for example – that can trap pollutants, such as those emitted from street-level traffic. Here, ventilation becomes critical, bringing a constant flow of fresh air to avoid a stagnant layer of contaminated air.

Figure 21 (Next page)

A visualisation of the Etobicoke Civic Center from above, illustrating how the rising building volumes and vegetated rooftops act as passive factors in mitigating local climatic conditions (Courtesy Henning Larsen)


WESTWOO

Conversely, in urban canyons that are shown to be relatively free of airborne pollutants, urban designers must consider wind-sheltering strategies to prevent contamination from neighbouring areas. Computational Fluid Dynamics (CFD) simulations can be used to analyse how building geometries influence the wind flow around buildings. Combining this with extensive, long-term analysis of street-level pollution provides urban designers with a basic road map of where to encourage urban ventilation and where to employ sheltering strategies.

Use trees. If trees are not blocking the wind, they are a great help in reducing air pollution. Trees absorb the greenhouse gas carbon dioxide, and their leaves capture and eliminate harmful nitrogen dioxide. However, not all plants are created equal in this regard. Finer, more complex structured foliage is most effective in capturing particulates. Conifers, for example, are effective because of their fine structure of hairy needles, but also because they are evergreen and therefore retain their function in the winter. They effectively act as a dense filter for airborne pollutants and can serve in this capacity through all seasons, where thinner, more seasonal plants effectively lose their functionality for large parts of the year. Common ivy – also an evergreen plant - is also good at capturing particulates, especially the finer fraction PM2.5 [1]. Understanding dominant particulates in an area, and analysing their pattern of distribution, must precede and inform designers' corresponding vegetation strategy.

H. C. ANDERSEN'S BOULEVARD, COPENHAGEN, DENMARK

The air pollution on H. C. Andersen's Boulevard, the busiest street in Copenhagen's city centre (Figure 22), far exceeds the permitted limits in the EU. Redirecting the 56,000 cars that pass down the boulevard each day is no easy feat as it would demand extensive reconstruction of vehicle traffic routes in the inner city. Instead, we must look to the finer details of urban design for a solution to the problem.

As detailed above, vegetation has an incredible ability to absorb pollutants. Beech and maple trees, for example, have the potential to absorb about 20 kg CO^2 per day. This adds up to 7 tonnes per year or the annual CO2 emissions from one Danish citizen (2014). The closer the plant is to the pollutant, the more effective it is at mitigating the pollutant's effects [2]. Along H.C. Andersen's Boulevard, installing a green base of dense shrubs and bushes at the same height as vehicle exhaust pipes would provide a critical, vegetated filter to combat this ongoing air pollution.

Benved (Euonymus) and Firewood (Pyracantha) were suggested, which are particularly good at the absorption of NOx and Ozone, and common Vedbend (Hedera Helix) is effective for absorbing CO2 emissions. Shrubs like these can only retain a portion of the absorbed pollutants, with rainwater washing approximately 60% of pollutants away. As such, underlying vegetation is also required to collect this runoff. Bioswales were suggested: long stretches of grass, sand, and soil that absorb polluted air while collecting and filtering rainwater, working in tandem with the filtering shrubs. The reduction of metal concentrations in bioswales ranges from 20-60%. Soil particles will attract and bind much of the remaining concentrations of the metals. If positioned directly adjacent to traffic lanes, these bioswales can also function as effective buffers between cars and cyclists, providing an additional benefit of commuter safety.

Figure 22

Copenhagen's H.C. Andersens Boulevard presents a notable local case study in exploring non-intrusive, design-based solutions to mitigating air pollution

Secure natural ventilation. Another solution in this scenario is to ensure that the polluted air is removed from street-level altitude, giving cleaner air for pedestrians. Despite natural countermeasures such as shrubs and bioswales, there will still be some degree of polluted air at street level – the trick is to steer it up and away, and to circulate cleaner air at the pedestrian level. A significant portion of H.C. Andersen Boulevard has rows of houses on both sides – These act like bumpers in a bowling alley, preventing exhaust-laden air from leaving the street level, and creating a built-up pocket of unhealthy air. To lift pollutants above the roofs, favourable channels for natural breezes were created, ensuring a good wind corridor to whisk pollutants away from street level.

Just like bushes, trees are efficient air purifiers, because they absorb carbon dioxide, release oxygen, humidify the air and filter it from pollutants. But trees can also hurt the wind flow if they are poorly positioned because dense treetops can trap unhealthy air in the street. The solution is to plant porous, relatively transparent trees so that the air can penetrate the branches, enabling filtration without obstructing ventilation channels [3]. Platanus (Platanus x hispanica) and Maple (Acer Pseudoplatan) were suggested, particularly good at the absorption of CO2, and NOx, and ozone beech (Fagus sylvatica) and Avnbók (Carpinus betulus), which absorb NOx and ozone.

Make room for alternatives. Give an advantage to efficient vehicles – We can help eliminate pollution at the source by incentivising the use of low-emission and space-efficient vehicles. For example, by eliminating two lanes out of the current six, each lane of which is estimated to be about three meters in width, we free up 600 m2 of the road for every 100-meter stretch of the boulevard. This could become fast lanes for buses, carpools, electric cars or perhaps wider bicycle paths, encouraging a greater share of daily traffic to emit fewer pollutants.

Many cities face problems similar to that of H.C. Andersen's Boulevard, where diverting or rerouting pollutant-heavy traffic is simply not a logistical or economic possibility. Here, we can turn to architecture and urban designers for less invasive, cost-effective solutions – Vegetation-based solutions, smarter ventilation, and incentivizing low-footprint transport alternatives. The air pollution on H. C. Andersen's Boulevard will not be solved overnight, but with the help of clever urban design, parts of the associated problems will be solved without necessarily redirecting traffic. Problems like this are only one part of a much larger equation regarding healthful urban environments – We must see them as an exercise in resourcefulness and smart design as we look to the details of our built environment to provide healthier, happier cities for future generations.

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ARCHITECTURE AS AN OUTDOOR AND INDOOR CLIMATE GIVER

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The practice of urban and building design, from concept to construction details, is currently shaped by city zoning and building codes, including energy ones. It is informative to remember that zoning was invented to facilitate, in dense anthropized areas, people's contact with surrounding environment (mainly through daylighting and fresh air intake), and, no less important, to separate discordant uses, shaping monofunctional neighbourhoods. Moreover, it is necessary to recall that most energy codes have profoundly changed the notion of contemporary building construction. In Europe, for instance, the Directive 2010/31/EU of the European Parliament, and of the Council of 19 May 2010 on the energy performance of buildings, are leading to the development of new buildings' technologies. However, strict zoning and energy codes have separated the design, and the climatic thinking, in two mono-focused scales: the larger city and the single building.

At the city scale, there has been, after the Second World War and until nowadays, a lack of focus on microclimatic design; areas have often been designed without considering bioclimatic criteria, making sites unattractive and ill prepared to cope with climate change. These decisions about urban form and building fabric have long-lasting, cumulative impacts on the liveability of outdoor spaces, and on the use of energy in buildings [1].

At the building scale, there has been no focus on buildings' impacts on the microclimate. The scope of codes and standard has been limited to maintaining constant indoor thermal neutrality and has disregarded any of the thermal effects on surroundings. In some cases, this has led to sealed buildings that exhaust the extracted heat into public spaces, further reducing the opportunities for outdoor social life.

It is thus clear that cities need new thermal and energy strategies to adapt to climate change, beyond those related to flooding or storm emergencies. This section tackles some insights related to the use of holistic simulation modelling to design urban resilience and adaptation elements, from new neighbourhoods to facade technologies.

It is past time that we rethink the city as a climatic continuum where urban spaces, also defined as 'outdoor rooms', and buildings are integrated to provide comfort and limit buildings' energy demand while providing wellbeing to inhabitants.

CHANGING CLIMATE, CHANGING ENERGY NEEDS

At any latitude, a considerable amount of energy, particularly electricity, is consumed for cooling buildings, and these conditions may worsen due to climate change, which induces warmer weather on average. A thorough study, performed for several locations across the world, has shown that – given the current climate change scenarios – by 2050 there will be an increase of the total cooling energy demand of commercial and residential buildings of approximately up to 250% and 750% respectively [2]. In another study it is predicted that there will be up to 17 (30) more days of tropical nights by 2060 (2100) in Switzerland [3]. It is thus evident that there is a need to increase the comfort and the design of buildings to adapt in the most comprehensive way to the negative impacts of climate change [3].

To give some dimension to the expected phenomenon, a completed study forecasts that the energy consumption for typical future years (2039, 2069, 2099) of the EPFL campus in Lausanne will significantly change [4]. With rising temperatures, the heating demand will decrease by 7% and 15% according to the climatic data for 2069 and 2099, respectively (when taking 2039 as the baseline). When looking at the cooling demand, the campus will face an increase of 30% and 52% in 2069 and 2099, respectively.

The value of this information is that it is deduced with careful modelling of the local microclimate's influence on energy demand. Building sustainable urban areas and bioclimatic buildings that will cooperate to mitigating the effects of climate change are thus key, and this requires the development of new tools able to relate future climate weather files and building design. The state of the art in building energy performance involves using a typical sample of weather based on historical records from the nearest weather station, which is often peri-urban or rural. Several recent studies have demonstrated the unsuitability of using only historical records for evaluating long-term design choice. Thus, the workflow featured in the next paragraphs uses specific techniques to use future weather prediction as well as to approximate the specific changes in conditions that can be recorded inside the city.

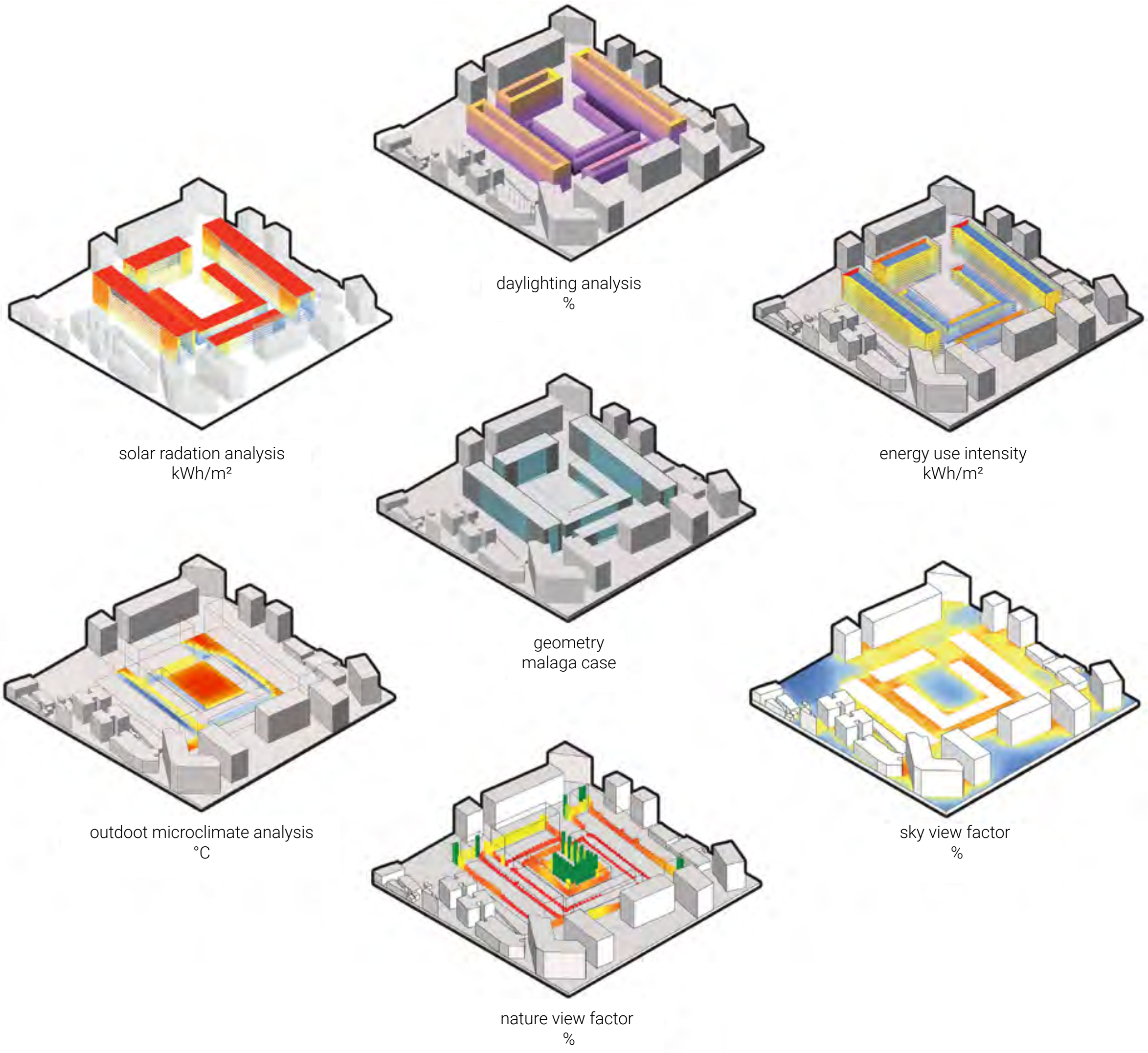


Figure 23

An overview of combined urban – buildings simulations. Both modification of the urban and the building design would lead to modification of local microclimate, access to sky view, connectedness to nature, indoor daylighting and building energy demand (Source [4])

DIGITALLY LINK CLIMATE, ENERGY AND WELLBEING

The responsive design of cities needs to go beyond climate change mitigation, i.e., reducing greenhouse gas emissions by reducing energy intensity, to adaptation, by which cities will be transformed into catalysts of a rich life, health and wellbeing. This approach will enhance the creation of a thriving ecosystem system by focusing on the improvement of the interdependent relationships between humans, built and natural environments. To prepare cities that are affected by placelessness, poor outdoor comfort and energy-devouring yet uncomfortable buildings, to face climate change, completed research has focused on developing an urban/building digital workflow that holistically tackles some of the significant urban issues.

It is known that urban or building design features affect at the same time outdoor comfort, building energy consumptions as well as the wellbeing of inhabitants and pedestrians. Only a few tools that have been developed in recent years for the assessment of multiple quantitate and qualitative factors. A remarkable example is the Urban Modelling Interface (UMI), a Rhino-based urban modelling design tool, which calculates operational energy use, embodied energy, daylighting and walkability at the urban scale. However, none of the existing multicriteria tools, at the time of writing, include outdoor comfort. To cover such a gap, a Grasshopper and Ladybug Tools workflow (Figure 23) was developed to allow holistic evaluation of choices related to space/building forms, material and operations [5]. The digital workflow, by leveraging synergies and interdependencies, allows holistically assessment of seemingly disparate environmental. A preliminary test with the workflow shows that measures that contribute to a suitable urban microclimate have substantial positive impacts on outdoor comfort, energy reduction and wellbeing.

DESIGN WITH MICROCLIMATE

It is recognised that linking microclimates and architectural design decisions have an essential effect on the energy performance of buildings. In his book *'Design with Climate'* (1963) [6], Victor Olgyay described how practitioners should be inspired by biology for the integration within microclimate, and by meteorology for a precise description of the climate. By using the findings from other sciences and applying them, Victor Olgyay showed how we could arrive at new climatic exactness by linking buildings to their broader context and the surroundings.

Almost 30 years later, Lechner (1991) [7] discussed how the sustainable design of heating, cooling, and lighting systems in buildings could be more easily accomplished by understanding the logic of a three-tier approach, of which the first and second tiers are deeply rooted in Olgyay's research. The first tier consists of integrating the local microclimate and could lead to up to a 60 per cent reduction of the heating, cooling and lighting energy demand. The second tier involves the use of passive heating, passive cooling, and daylighting systems planning. Proper decisions taken at this point can reduce the energy demand by a further 20 per cent. Thus, according to Lechner, the strategies in tiers one and two, both purely related to climate, site and building design, can reduce the energy demand of buildings by up to 80 per cent. When Olgyay wrote his book, building energy simulation was at its inception, whereas when Lechner made his claims, energy simulation only allowed for a small number of simulations with simplified building models.

Recent research found that the energy saving potential of bioclimatic design decisions varies from 63 to 76 per cent depending on the climate [8]. Digital workflows should thus be aimed at designing buildings that operate within their microclimates.

LADYBUG TOOLS COUPLING OUTDOOR AND INDOOR

Whereas it is known that outdoor and indoor spaces are interconnected by conductive, radiative (short and long wave) and convective phenomena, this has seldom been considered in urban design. Although several algorithms and tools (like Envi-Met and CitySim among others) are already used in research and professional practice in understanding the effects of buildings on outdoor microclimate, there is a lack of tools properly integrated with software for architectural design and indoor microclimate assessment. Recently, Ladybug Tools, under the work of Chris Mackey and Mostapha Roudasari, has introduced workflows that allow the simulation of outdoor comfort. Outdoor thermal comfort is related to the calculation of outdoor Mean Radiant Temperature (MRT), a key parameter at the base of the Universal Thermal Climate Index (UTCI) [9]. The calculation of MRT is simulated by first computing longwave MRT based on ground and building surface temperatures calculated with EnergyPlus. View factors of surface are calculated with the ray-tracing capabilities of Rhino 3D. The temperature of each building surface viewed from the face of a target point is calculated as a weighted temperature, where the weight is defined by how much surrounding surfaces are viewed by the face of a given point.

Figure 24

A comparison of MRT calculated with the Ladybug Tools workflow and measured on site for a location in Copenhagen. Along the four days of measurement, a good agreement was recorded

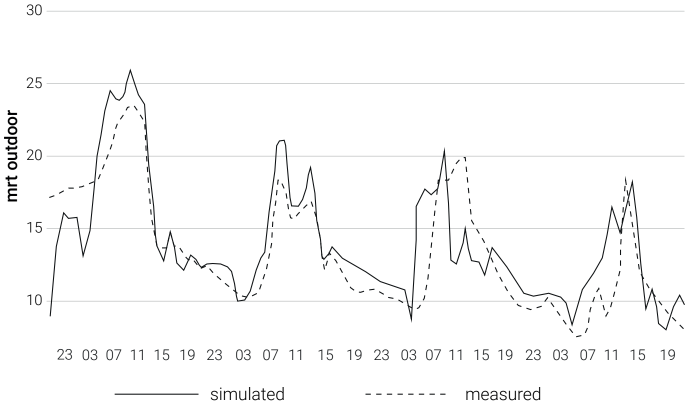
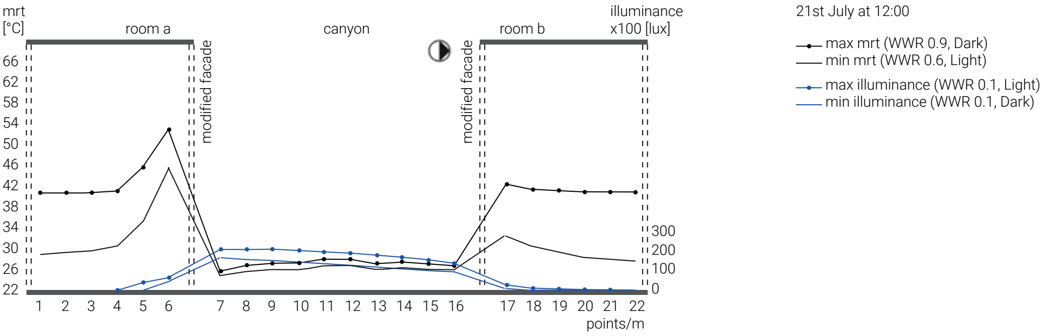


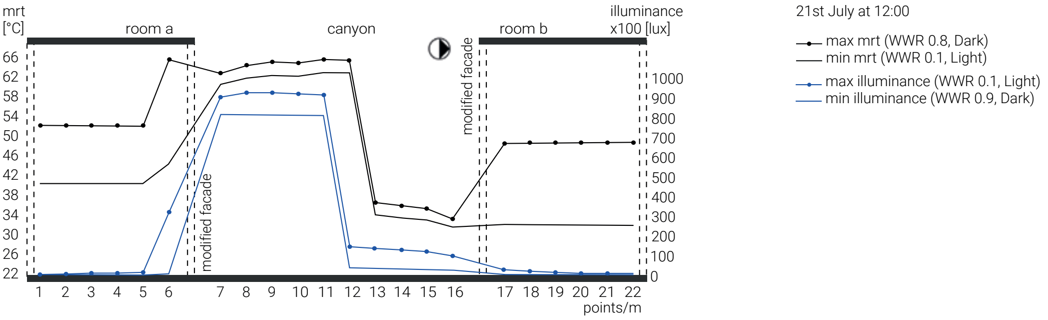
Figure 25

The test room located at KADK campus in Copenhagen. Several façade types can be installed. MRT and illuminance levels can be recorded simultaneously in both the front facing the street and in the room. The facility was used to validate the 'Façade as Dual Climate Giver' workflow in Ladybug Tools

The outdoor calculation considers the sky temperature and the consequent longwave loss to the sky. The calculated longwave MRT is then adjusted to account for shortwave solar radiation that falls on people using the SolarCal model, which is a part of ASHRAE-55 thermal comfort standard [10].

Customised workflows that couple the outdoor and the indoor can be created [10] by linking the outdoor comfort scripts to the indoor comfort and energy calculations using Ladybug Tools. This allows simulating how buildings and 'outdoor rooms' affect the local microclimate, the indoor microclimate and the building energy demand. This is a step forward as outdoor comfort tools and building energy modelling tools are generally unconnected. Practitioners can now appreciate the thermal influence of the outdoor space towards the interior, and vice-versa. Given its novelty, the workflow still needs extensive validation. However, preliminary research found that the workflow offers good agreement with measured data [11-13] as shown in Figure 24.





FAÇADE AS DUAL - INDOOR AND OUTDOOR - CLIMATE GIVER

Within the bounds of climate change, it is legitimate to expect that buildings will be developed to mitigate and adapt to environmental transitions. In this context, façades are essential as they can influence the way heat and light are absorbed, reflected and re-emitted toward the outside and the inside.

Façades are most of the time studied for the indoor control of thermal and luminous comfort. While there is a vast literature on the influence of the envelope on the indoor, there is only a handful of research on the influence on the outdoor. Given the importance of promoting outdoor life in urban areas, a series of the study was aimed at understanding to what extent a façade can influence the outdoor.

Facades constitute an essential element in an urban site, transforming the 'outdoor rooms' microclimate, which in turn has an impact on building energy demand and indoor comfort. Designing to optimise the thermal comfort of both outdoor spaces and the indoor is a crucial role of the façade. Façades can thus be intended as dual climate givers for both the outdoor and the indoor.

A digital workflow to conceive façades as dual climate givers has been created [14], and can be used to support the design of the façade calculating at once the outdoor rooms' comfort (the open space), the indoor rooms' comfort and the energy consumptions. The workflow was validated against measurements taken in a façade testing facility, where sensors were positioned on the street, in the wall and the indoors (Figure 25).

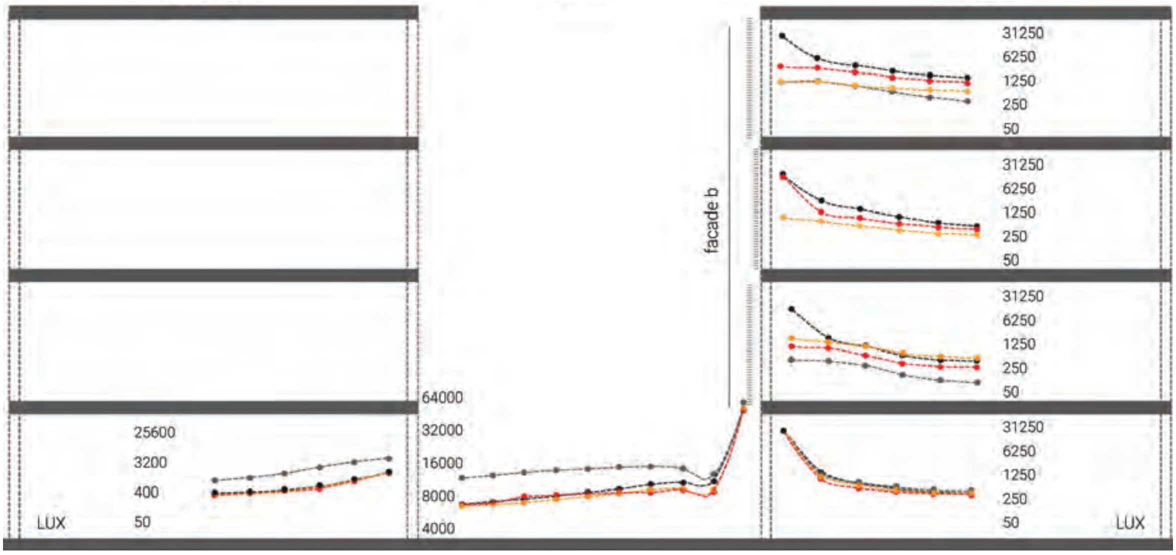
Figure 26

Variation of Mean Radiant Temperature and Illuminance in Madrid when facade colour and Windows to Wall Ratios are changed. MRT can be reduced by 2 degrees (Source: [12])

The created ability to co-simulate outdoor and indoor rooms led to some preliminary experiments run in order to evaluate how the design of a façade can impact them. A preliminary work tested how variations of the window-to-wall-ratio (WWR) and the colour of the outermost surface of the façade located in Copenhagen and Madrid impact outdoor and indoor MRT and illuminance (lux). The simulation proved that façade choice could significantly impact the outdoor and indoor rooms' thermal and visual comfort (Figure 26 and 27). It is shown that in Copenhagen streets, MRT can be increased by 2 degrees depending on the façade type, leading to milder winters. In Madrid, MRT can be reduced to 4 degrees in summer, leading to cooler streets.

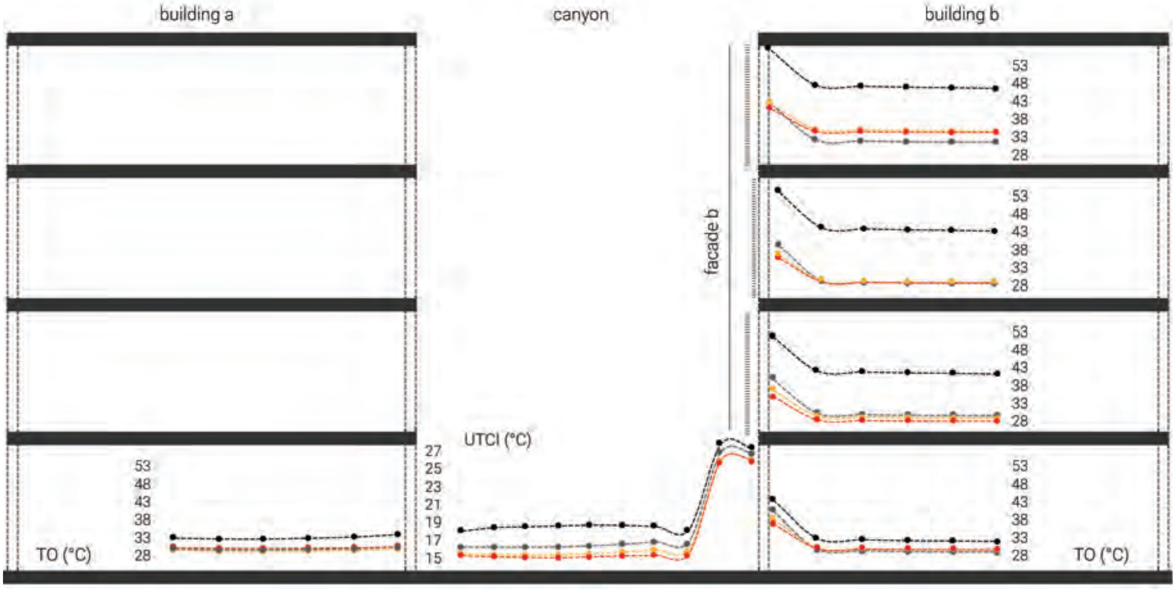
Figure 27

Variation of Mean Radiant Temperature and Illuminance in Copenhagen when facade colour and Windows to Wall Ratios are changed (Source: [12])



results - daylight 15:00 4th august

- ● no shading
- ● steady state
- ● dynamic venetian blind
- ● adaptive facade
- ═ the applied adaptive facade



results - thermal comfort 15:00-16:00 4th august

- ● no shading
- ● steady state
- ● dynamic venetian blind
- ● adaptive facade
- ═ the applied adaptive facade

Figure 28

Variation of Mean Radiant Temperature in Copenhagen when façade types are change. It should be noticed that different façade technologies applied in building B's upper floors influence both the canyon and the front facing building temperatures (Source: [13])

Another work shows how four types of typical façades, including no shading, static shading, dynamic and adaptive solutions, when applied to the street canyon in Østergade, Copenhagen, perform in relation to outdoor and indoor comfort [15]. The simulated metrics are the universal thermal comfort index (UTCI) for the outdoors space and the operative temperature for the indoor (Figure 28). Illuminance values (lux) are used to detect light distribution (Figure 29). The design of the façade was found to affect the urban thermal and visual environment and especially the centre of the canyon, where people usually walk through.

It is here noted, probably not surprisingly, that glazed surfaces increase street temperatures. However, shading systems decrease the perceived temperature not only in the indoor environment of the building but also in the direct vicinity of the façade, the street and the front facing building interiors. For the Illuminance, it is the opposite. Shading surfaces increases street illuminance. However, for illuminance levels, the contingent angle of reflection has an impact on outdoor illuminance levels.

It is thus clear that a façade could be designed in order to regulate outdoor rooms' thermal and visual comfort, and this can be adjusted to satisfy outdoor and indoor human activities. This experiment shows that façades could be programmed to assure comfort both in the indoor or the outdoor, leading to interesting scenarios of developments; what if façades are set into configurations that prioritise outdoor or indoor comfort selectively and dynamically?

Figure 29

Variation of Illuminance in Copenhagen when façade types are changed. It should be noticed that different façade technologies applied in building B's upper floors influence both the canyon and the front facing building temperatures (Source: [13])

UTCI AND BUILDING ENERGY CO-OPTIMIZATION

A final study was then conducted using the Ladybug workflow to study strategies that could minimise the thermal stress induced by the heavy Urban Heat Island (UHI) affecting the city of Catania, in Sicily [12, 13]. The UHI is expected to upsurge with climate change if no mitigation actions are taken. Furthermore, cooling loads are progressively increasing to the extent that the energy network fails to provide the necessary energy. The study thus tries to explore how it is possible to reduce summer UTCI while reducing building energy demand (Figure 30 and Figure 31).

Such co-process would celebrate the idea of places that fully embrace climatic differences. At a time when globalisation and continental standardisation of codes have contributed to a sense of placelessness in the modern metropolis, a climate-responsive approach to urban planning and façade design should manifest a reading of different human activities and geographic conditions.

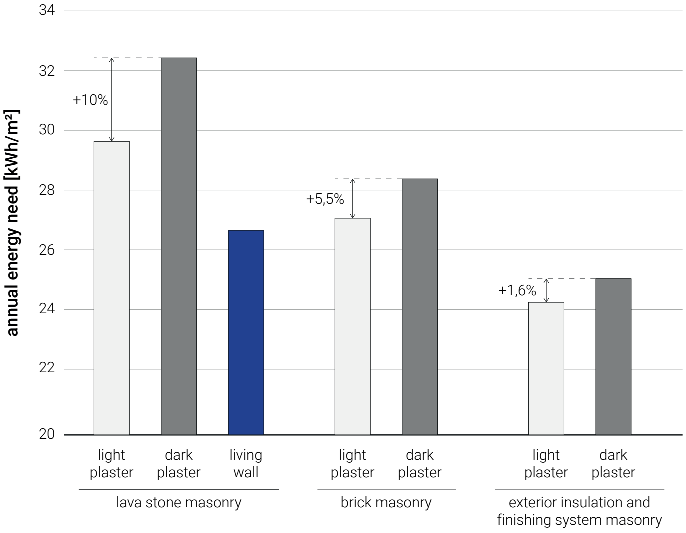


Figure 30

Comparison between annual energy needs of three wall types. The lava stone is the material of the oldest buildings built in the 1920s. The calculation is based on the Ladybug Tools workflow and accounts for the local microclimate interaction with the buildings (Source: [11])

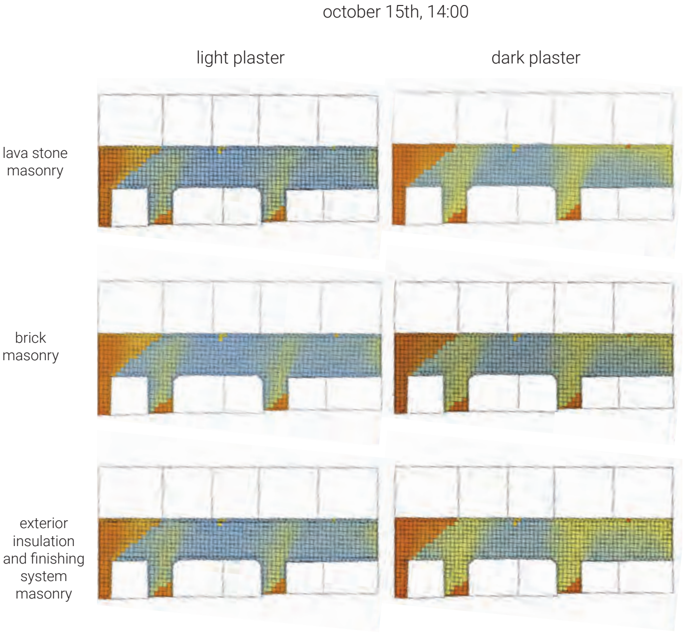


Figure 31

Comparison between UTCI values for dark and light plaster applied on the existing lava stone masonry in April and October (Source: [11])

Placelessness would be replaced by the distinctive evolution of each city's built form and façade types customised to support climate change issues and residents' health, well-being and access to affordable energy units. These preliminary experiments show that only focusing on parameters, such as setbacks, height, build-to lines, of zoning codes, and only energy performance at the building scale is misleading. Looking forward, planners and designers need to design interlocked climatic outdoor and indoor rooms while paying attention to minimising the use of energy. This can now be supported by the shown workflows.

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CLIMATIC PERFORMANCE OF COOL AND GREEN ROOFING

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Urban Heat Island (UHI) effects are one of the consequences of climate change that mostly affect daily life in densely populated cities by worsening thermal comfort conditions and increasing health risks. However, the interconnections between the UHI effects and the built environment are mutual and not easy to comprehensively characterise due to several trade-offs. This paper aims to cast some light on the issue by proposing a comparison between cool and green roof technologies when applied as passive cooling strategies in existing buildings. Despite both technologies allowing the reduction of heat exchanged through the roof, and cleaning of the air while reducing rainwater runoff in the case of green roofs, the use of a dynamic thermal model calibrated with experimental measurements allowed further insights into the building's thermal behaviour, thus providing a more time and cost effective method than performing extensive field experiments.

The results obtained show that both cool and green roofs are reasonable solutions from a regenerative design perspective. The roof surface temperature can be reduced by up to 30°C if compared to a traditional roof-finishing layer when a high-performance cool paint is used. This fact has the potential to reduce health risks when heat waves occur in summer. Further, green roofs act as a shading and insulating layer at the same time, so they improve the annual building thermal behaviour by reducing the energy consumption for space heating and cooling. These outcomes can be extended to similar buildings under comparable climate conditions and thus inform policymakers when planning regenerative design strategies for cities.

Under this perspective, Tan et al. [1] demonstrated that in high-density subtropical cities, urban greenery could contribute to the reduction of air temperature by 1.5°C. More specifically, the application of some greenery to roof surfaces represents the best performing passive strategy for reducing the urban temperature as they can be applied to a large number of urban surfaces. Other strategies usually rely on the application of highly reflective coatings to roofs (that is, cool roofs) and other parts of the buildings' envelope [2-6]. Their application proved to reduce the peak air temperature in a dense urban arrangement in Athens (Greece) by about 1–2 °C [7], and also to strongly reduce the cooling energy needs of a building located in southern Italy [12].

However, previous studies have focused their attention mainly on the roof behaviour in summer. As far as the winter period is concerned, these solutions might create a reduction in the solar heat gains through the roof, and hence produce an increase in the building energy needs for space heating even in warm climates. To cast light on this issue, the present paper shows the results of annual dynamic simulations conducted in EnergyPlus for an office building located in the hot and humid climate of Catania (Italy, LAT. 37°31'N). The optimal range of applicability of both green and cool roofs is given by comparing the energy performance and the external roof temperatures of five scenarios: i) the existing roof (base case), ii) green roof without irrigation (GR_1), iii) green roof with an irrigation schedule (GR_2) and iv-v) cool roofs with two different solar reflectance values (r = 0.65 for CR_1 and r = 0.80 for CR_2 respectively).

THERMAL SIMULATIONS OUTCOMES

The energy assessment of the different solutions analysed is based on the concept of Primary Energy Ratio (PER): this is defined as the ratio of the thermal energy delivered from (or extracted from) the conditioned space to the Primary Energy consumption of the specific air-conditioning device used. The simulations revealed that the use of an extensive green roof equipped with an irrigation system (GR_2) can lead to a reduction of about 10% of annual primary energy needs for cooling and heating when using an air-to-water heat pump in winter, or by about 8% when using a gas-fired boiler (see Figure 32). On the other hand, the application of the cool paint was the best solution for reducing the cooling energy needs, as can be observed in Figure 32, in which the cooling energy needs are considerably reduced (by about 17% for CR_1, and by about 25% for CR_2). This is due to the insulating potential of green roofs' soil layer that reduces the energy needs in winter, whereas cool roofs may lead to an increase in the energy consumption for space heating since they reduce solar heat gains.

Looking at the roof temperatures achieved in a whole year, the frequency distribution plotted in Primary Energy (PE) consumption results split for the heating and cooling seasons, are presented for different simulation scenarios involving the use of a gas-fired boiler or heat pumps as HVAC systems

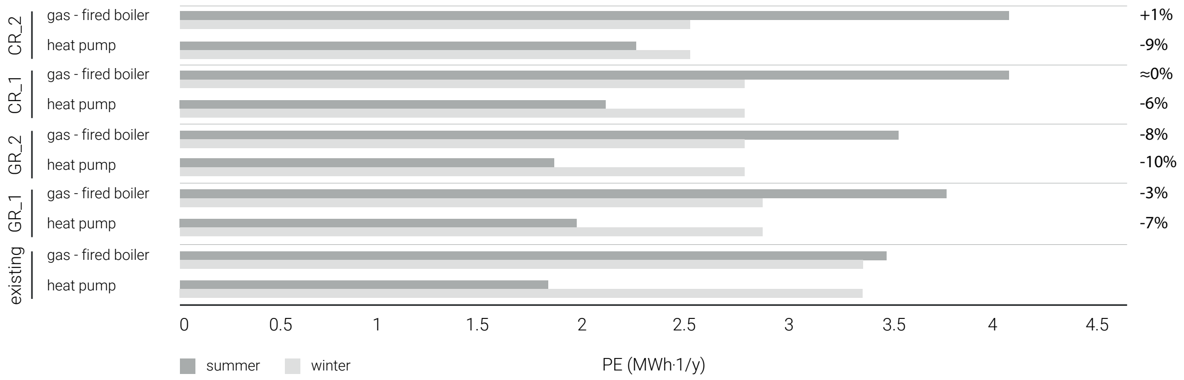
Figure 32
Primary Energy (PE) consumption results split for the heating and cooling seasons, are presented for different simulation scenarios involving the use of a gas-fired boiler or heat pumps as HVAC systems

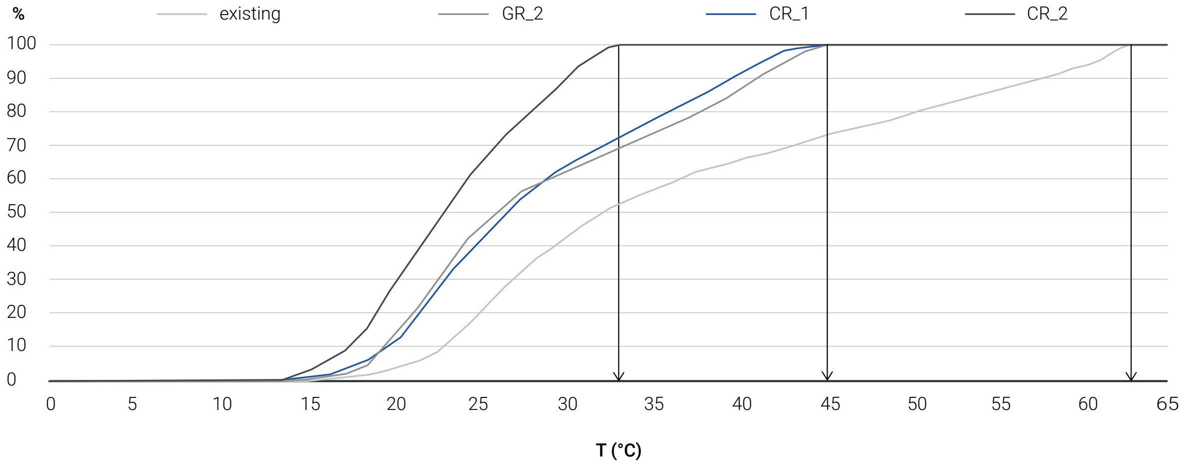
Figure 33 shows how the external roof temperature is always below 45 °C if green or cool roofs are used, whereas in a traditional roof covered with clay tiles (existing case) the external temperature would exceed this threshold 25% of the time, and it would even reach a peak of about 60 °C in the hottest days. The results referring to CR_1 and the green roof solutions are similar, with a slight preference given to GR_2. However, when a coating with high solar reflectance is used (CR_2, solar reflectance value of 0.85), the reduction in the external roof temperature is more significant: in fact, the peak value does not exceed 35 °C, and for 80% of the time the temperature is even below 28 °C.

Figure 33
The cumulative frequency distribution of roof temperatures is presented for the existing base case scenario (light grey line), green roof (blue line) and two different cool roof solutions (grey and dark grey lines)

The results of the simulations show that cool roofs are the most suitable solution for reducing the external roof surface temperature. Indeed, if using a high performing cool paint with r = 0.8, peak reductions ranging from 15 to 25 °C in summer should be expected, but during the afternoon and evening the effect is less pronounced. Green roofs follow a similar trend, at least if compared to cool paints with an average cooling potential (r = 0.65). This is important from a health perspective due to the potential to reduce heat stress conditions experienced by people living on the top floors, who are the most affected by heat waves.

On the other hand, looking at the annual primary energy needs of the sample building under analysis, green roofs are preferable to cool roofs because of their combined shading and insulating action provided by the foliage and soil layer, respectively. In conclusion, depending on the perspective that drives the comparison, the choice between cool and green roofs can vary: if looking only at the issue of UHI effect mitigation, cool roofs (especially those with very high solar reflectance values) are preferable. Conversely, if looking at the annual primary energy needs of buildings, green roofs perform better. These conclusions can be used by policymakers to inform the choice among different and somewhat contrasting regenerative design options.


CR_2
gas - fired boiler
heat pump
CR_1
gas - fired boiler
heat pump
GR_2
gas - fired boiler
heat pump
GR_1
gas - fired boiler
heat pump
existing
gas - fired boiler
heat pump
+1%
-9%
≈0%
-6%
-8%
-10%
-3%
-7%
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
summer
winter
PE (MWh·1/y)


%
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GR_2
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60
65
T (°C)

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PLANNING LOW-CARBON CITIES: THE CITY ENERGY ANALYST

Jimeno A. Fonseca, Uta Gelbke, Arno Schlueter *ETH Zürich, Switzerland*

In 2015, the UN conference on climate change in Paris concluded with a revolutionary agreement. For the first time in history, 195 nations, committed to actively reduce their carbon footprint. The event has changed the agenda of many nations about investment in clean technology and energy efficiency, especially in cities, which are at the epicentre of the consumption of non-renewable and highly contaminating sources of energy.

The change in the agenda of most nations towards a low-carbon society comes a time of extreme population growth. To accommodate more people, entire districts are being rejuvenated or newly built to feature a denser set of building types and functions. This sudden change challenges the infrastructure of energy systems that need to cope with new and increased needs of energy demand while also needing to be carbon neutral, if not carbon positive.

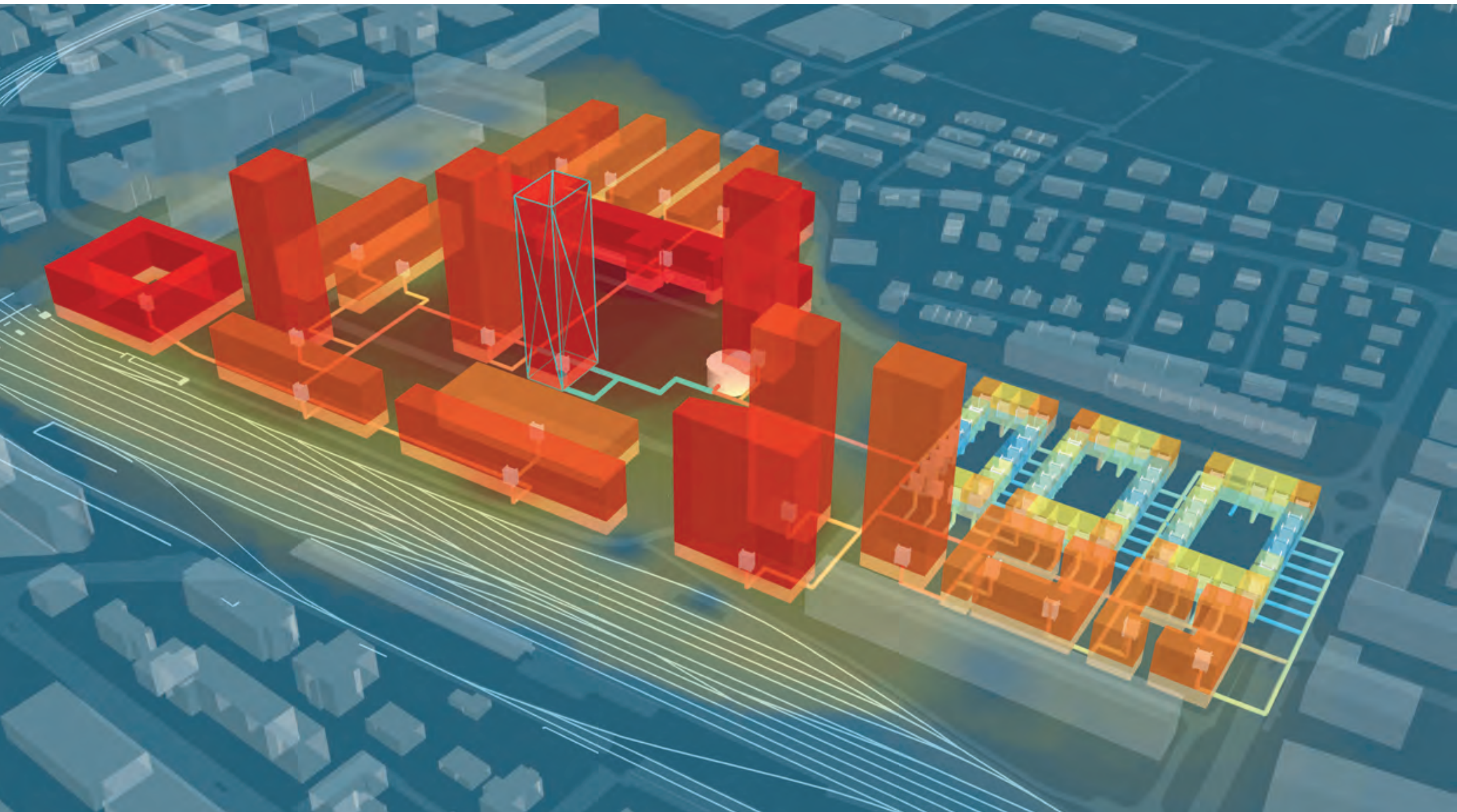
It is thus of importance to have holistic toolsets to design low-carbon neighbourhoods, most notably tools that could account for interactions between disciplines such as urban design, building systems and process engineering. As part of our research at ETH Zurich and the SEC Future Cities Lab Singapore, the authors of the contribution have created The City Energy Analyst (CEA), one of the first open-source tools for the design of low-carbon and highly efficient districts.

THE SYNERGIES AMONG USES, URBAN FABRIC AND ENERGY SYSTEMS

In line with Modernist urban planning concepts, newly planned districts were often divided into separate mono-functional zones and uses (e.g., purely commercial areas separated from residential). Though gaining much approval at first, the major shortcomings of mono-functional districts, such as the resulting increase in traffic and the neglect of human scale, soon became apparent. Consequently, in recent years, mixed-use and diversity have become key elements of urban planning schemes. Integrating the development of district energy infrastructure into mixed-use urban planning requires a deep understanding of the interactions and synergies between the urban form and energy systems. Previous research has indicated the high potential that energy efficiency integrated into urban planning practices might bring for mitigation and adaptation to climate change.

Conversely, it has reported the high uncertainty that this practice brings when planning for long time horizons without addressing emergent behaviour. Coupling urban design, building systems and process engineering expertise will allow planners to harness the even more substantial potential for increased sustainability. Successes in this sector can support significant positive change in the total consumption and emissions, potentially leading to meeting the regenerative design targets of cities that are energy and carbon neutral or even energy positive.

Figure 34
An urban design and energy infrastructure scenario with the City Energy Analyst tool



THE CITY ENERGY ANALYST TOOL

The City Energy Analyst (CEA) (Figure 34) combines aspects of urban planning and energy systems engineering in an integrated simulation platform. The CEA tool strives to empower urban designers and energy engineers to create holistic designs for low-carbon cities. Also, it aims to allow researchers to use state-of-the-art models and databases to forecast, analyse and optimise the demand and consumption of energy services in cities. These databases and models drastically speed-up the complex process of simulating and analysing several hundreds of buildings.

In more detail, the CEA enables the study of effects, trade-offs and synergies of urban design options and energy infrastructure plans. In hourly time-steps, the CEA calculates the combined processes of generating, distributing and consuming energy for a given urban design scenario. It allows planning teams to create multiple scenarios, visualise them in time and space and determine which scenario improves the costs, emissions and energy efficiency the most for their district.

Hence, the tool uses state-of-the-art computational models for forecasting the building demand, assessing the availability of renewable energy, actuating the simulation of conversion, simulating storage and distribution technologies, and performing the optimisation and multi-criteria assessment of energy systems. For visualisation purposes, the CEA can be connected to a geographic information system (Esri ArcGIS) and more recently to the Rhino and Grasshopper environment. This feature allows practitioners to introduce strategies of energy efficiency to a non-expert audience more easily.

The CEA is built in a modular structure so users can quickly get feedback on their simulations through visualisation. The framework consists of a demand module (1), a resource potential module (2), a systems technology module (3), a system optimisation module (4), a decision module (5) and a spatiotemporal analysis module (6). The detailed features of each module are further discussed in [1]. Each of these different modules assists the users in analysing the effects of one or more of the next strategies to plan low-carbon districts (see Figure 35):

- Building Retrofits: appliances and lighting, building envelope, HVAC systems (including control strategies).
- Integration of Local Energy Resources: renewable and waste-to-heat energy sources.
- District Energy Networks: decentralised and centralised thermal micro-grids and conversion technologies.
- Modifications to Urban Form: new zoning, changes in occupancy and building typology.

APPLICATIONS AND USE CASES

The CEA has been used in various case studies on integrating urban energy systems around the world. The transfer and application of real-world cases allow important questions of feasibility and economics to be addressed and synergies to be leveraged. Three examples that display the applicability of the tool are introduced below.

Singapore, Ecocampus. The Nanyang Technological University (NTU), Singapore's EcoCampus Initiative aims to be a leading example of high impact energy efficiency and sustainability for urban developments in Singapore. The goal is to achieve a 35% reduction in energy, carbon, water and waste intensity. The initiative encompasses the NTU Campus as well as new developments in the neighbourhood. The CEA is used in the project *'Urban infrastructure optimisation for the Eco-Campus project'*. The work, developed with the industry partner VEOLIA, studies a framework for the analysis and prediction of the energy demand and emissions of the NTY campus by 2020.

Zurich, University Campus. The university district *'Hochschulquartier'*, located at the centre of Zurich, is home to three institutions in research, education and health: ETH Zurich, the University of Zurich and the University Hospital Zurich. The area is being regenerated as an internationally competitive location for knowledge and health with an increase in usable floor space of 40%. To realise this growth and redevelopment in a dense urban area, the interests and demands of the three key stakeholders have to be considered and coordinated. The ETH, the University of Zurich and the University Hospital are thus exploring the potential synergies for sharing land and services, balanced with the use and expansion of green spaces that are of high relevance for the area. Here, the CEA is used in the project *'SPACERGY'* [2] to analyse the effect of urban planning measures on energy demand in terms of quantity, quality (supply temperatures) and dynamics. The tool is used to define the necessary infrastructure for tiering new energy sources and demands to a century-old energy distribution network.

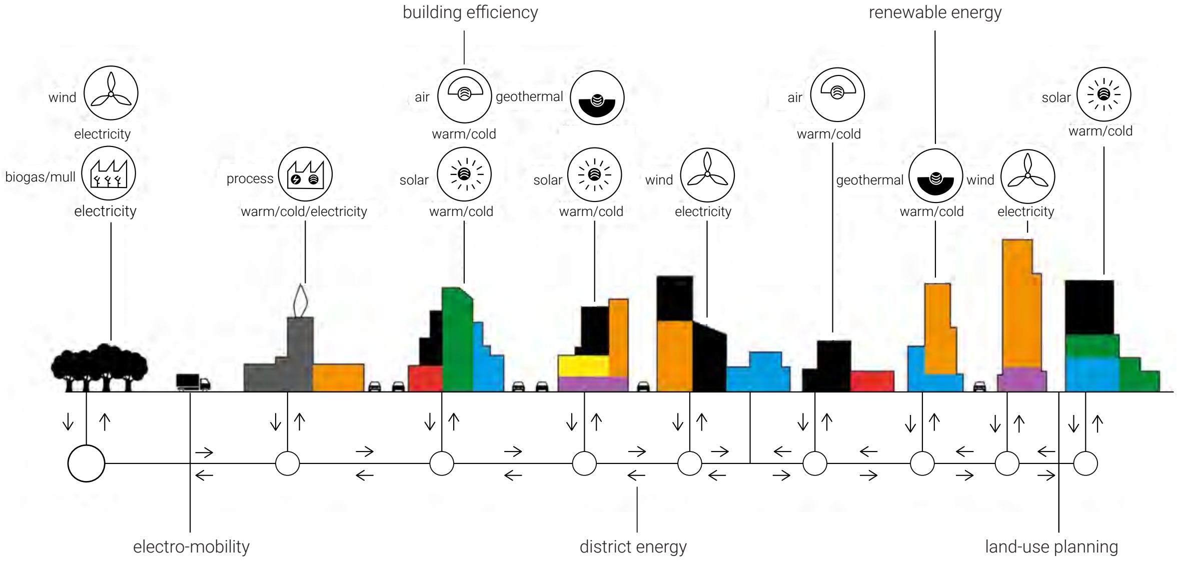


Figure 35

Strategies for the low-carbon city to be explored with the City Energy Analyst

Almere, Floriade legacy >2022. Amsterdam's metropolitan area is facing an explosive population growth over the next twenty years. Within this expansion, the Municipality of Almere will realise the most substantial portion of new developments, including 60 000 new homes. Almere has the ambition of increasing its size while also increasing the quality of life for its inhabitants, including ambitious plans regarding sustainability. The legacy of the site of Floriade 2022 (the world's largest horticultural expo) in Almere will be co-developed as a green extension to the city centre with the theme *'Growing Green'*. The proposal creates an energy-neutral, mixed-use residential area that directly integrates a grid of 'gardens' into the built environment. As part of the 'SPACERGY' project, the CEA is used to analyse the effect of building form and vegetation on the area's energy demand.

There is a great commitment of many nations to respond to climate change by reducing the carbon footprint of their cities. New city districts and their energy systems will need to be designed to not only cope with high rates of urbanisation but also to guarantee the integration of low-carbon infrastructure. The City Energy Analyst was developed as one of the first open-source initiatives looking at facilitating the design of low-carbon cities in a holistic way. Today, the tool is applied in a variety of case studies in Europe and Asia and has the potential to turn into an essential planning instrument when aiming to stretch the goals of a low-carbon city to a fully carbon-positive and regenerative city.

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DIGITAL INTEGRATIVE URBAN PLANNING

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Reinhard Koenig *Bauhaus-University Weimar, Germany*

By 2050 an estimated 70 per cent of the world‘s population will live in megacities with more than 10 million citizens [1]. This growth requires innovative, efficient and interdisciplinary digital methods for planning. The need for target-oriented, regenerative and efficient urban planning and design in cities is continuously growing due to progressive urbanisation that diverges from sustainable targets.

A contemporary urban planning process demands human-centred development, where future technologies are intertwined with traditional approaches. Innovative design, parametric planning, digital tools and the experience of experts and executive planners allow the fostering of designs that can restore the quality of compromised ecosystems. A smart digital environment, supporting informative decisions and facilitating the exchange of information between stakeholders to design the built environment and public realm, is thus key.

The presented workflow includes analyses and simulation tools within Rhinoceros 3D and the parametric plug-in Grasshopper as quality-enhancing mediums that enable the achievement of regenerative performance, facilitating creative approaches in the course of the project. Compared to traditional GIS-based planning software, the use and application of parametric modelling techniques require a knowledge of the individual parameters used and the digital data workflow [2].

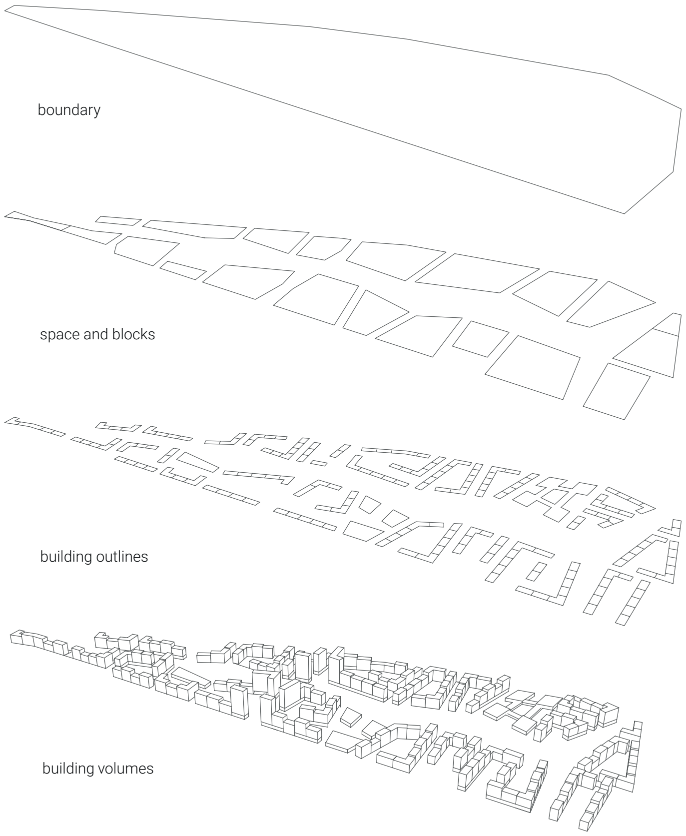


Figure 36
Integrative procedural urban planning and design workflow to create an adaptive masterplan

The application of procedural modelling techniques within the urban planning process assists in creating a sustainable, liveable public realm while saving time and resources. Procedural modelling means a rule-based generation of three-dimensional (3D) models based on a set of parameters, which, about urban planning, include the creation of data-informed master plans that are either based on evaluation results or set manually (see Figure 36).

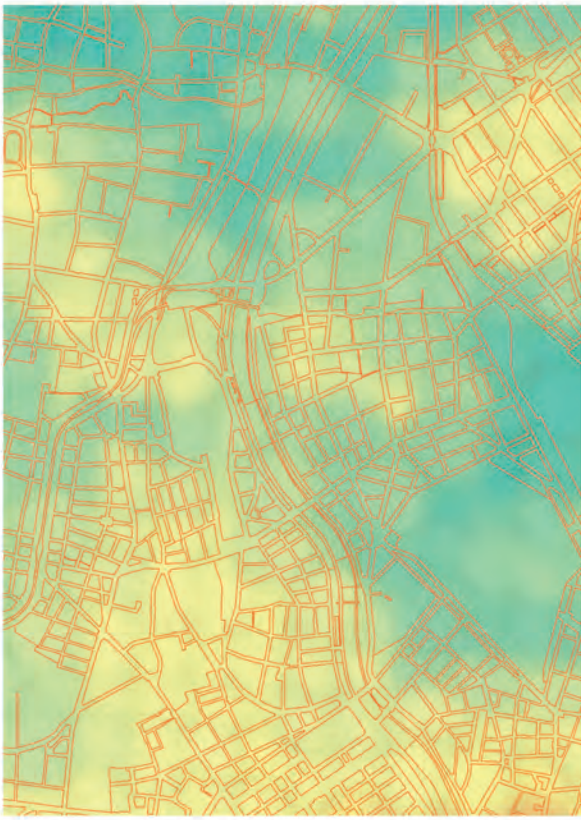
The main benefit of this approach is the enormous saving of time compared to modelling in a non-procedural. Thus, the approach brings the possibility to explore more design variants, which may lead to a consequent reduction of design costs [3] and an increase of the spatial design qualities. The performance-based computational design supports spatial analysis, synthesis and evaluation that mainly focuses on the performance during the design process [4].

Figure 37
Urban attractiveness maps on proximity to amenities

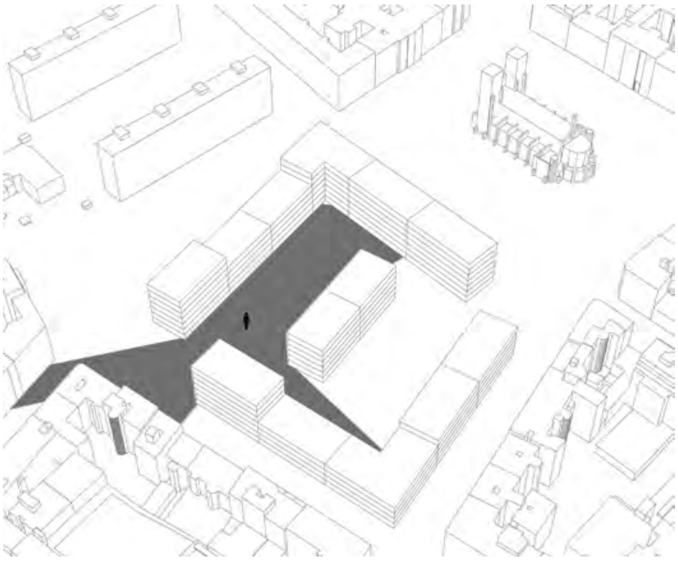
public transport attractiveness

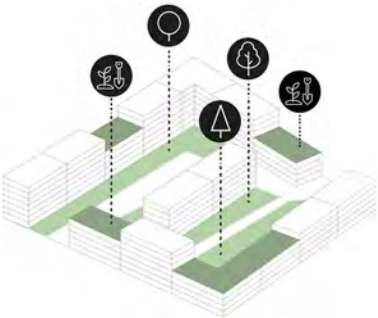
educational institutions attractiveness

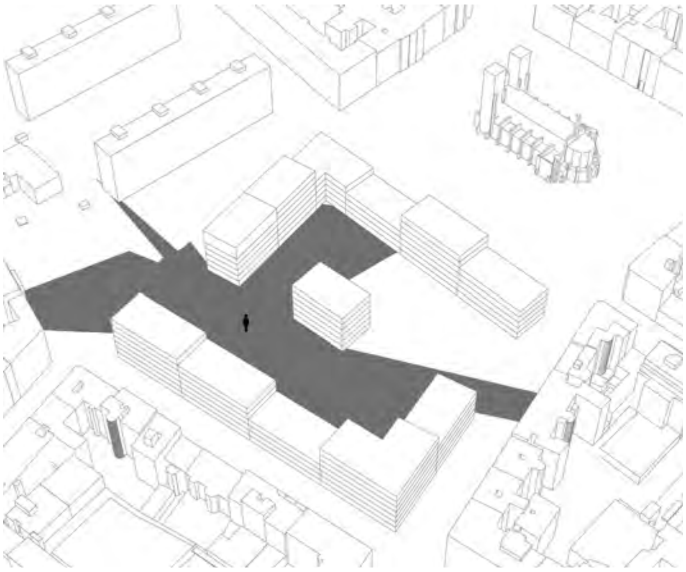
local supply attractiveness

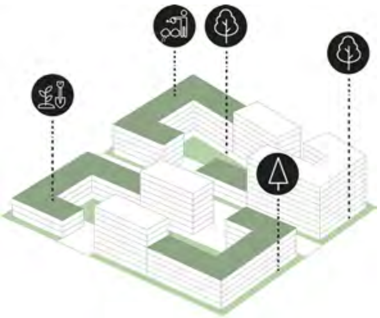


cultural attractiveness









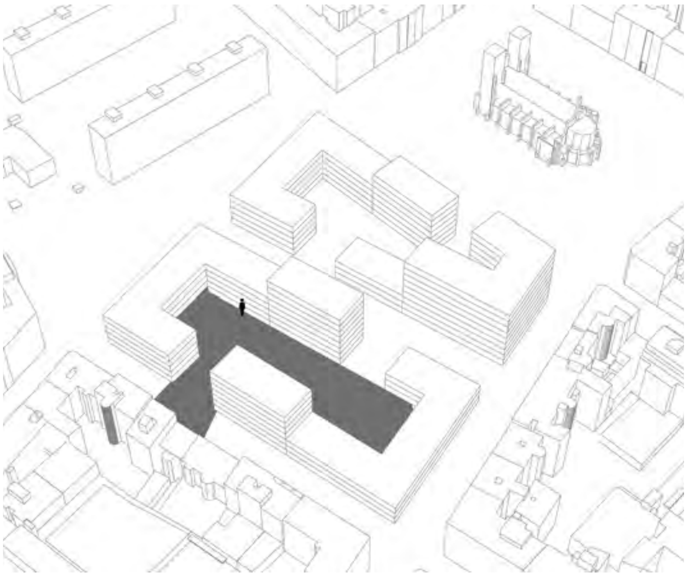


Figure 38
Isovist analysis illustration (left)

Figure 39
Parametric generation of buildings, including vegetation for microclimate analysis (right)

PARAMETRIC DESIGN TO LEVERAGE EXPERTISE INTEGRATION

New tools allow the simulation of different qualities based on parametric and algorithmic processes to capture the city with all its layers [5]. Parametric thinking is not a method to find a single solution, but to show the different possibilities by using algorithms and modern calculation techniques [6], and thus can be considered as a new design method. A flexible, integrative urban planning workflow that is based on experts' experience is described to provide an overview of a possible planning course. To validate and evaluate the potential of this approach, the workflow was applied on a master plan in Vienna that offers (besides cultural, social and urban qualities) a wide range of open data on infrastructure, demographics and the built environment.

The parametric workflow allows for a spatial analysis that includes the flows given by traffic, the mix of uses, microclimates, district energy use and human-centred metrics (e.g. view factors)(see Figure 38). These are key parameters that can be calculated and evaluated for various proposals supporting information-based decision management. The site simulations go beyond the conventional methods belonging to traditional urban planning in order to include the evaluation of proximity to amenities, vegetation and an accessibility analysis for both the existing and the design street network, in which the output is defined by betweenness and closeness centrality that reveal the attractiveness (see Figure 37, 38 and 39), potential and challenges of locations. Accessibility, visibility, microclimate, solar radiation, energy and further parameters could thus be simultaneously combined in the workflow and more instances can be added (see Figure 40).

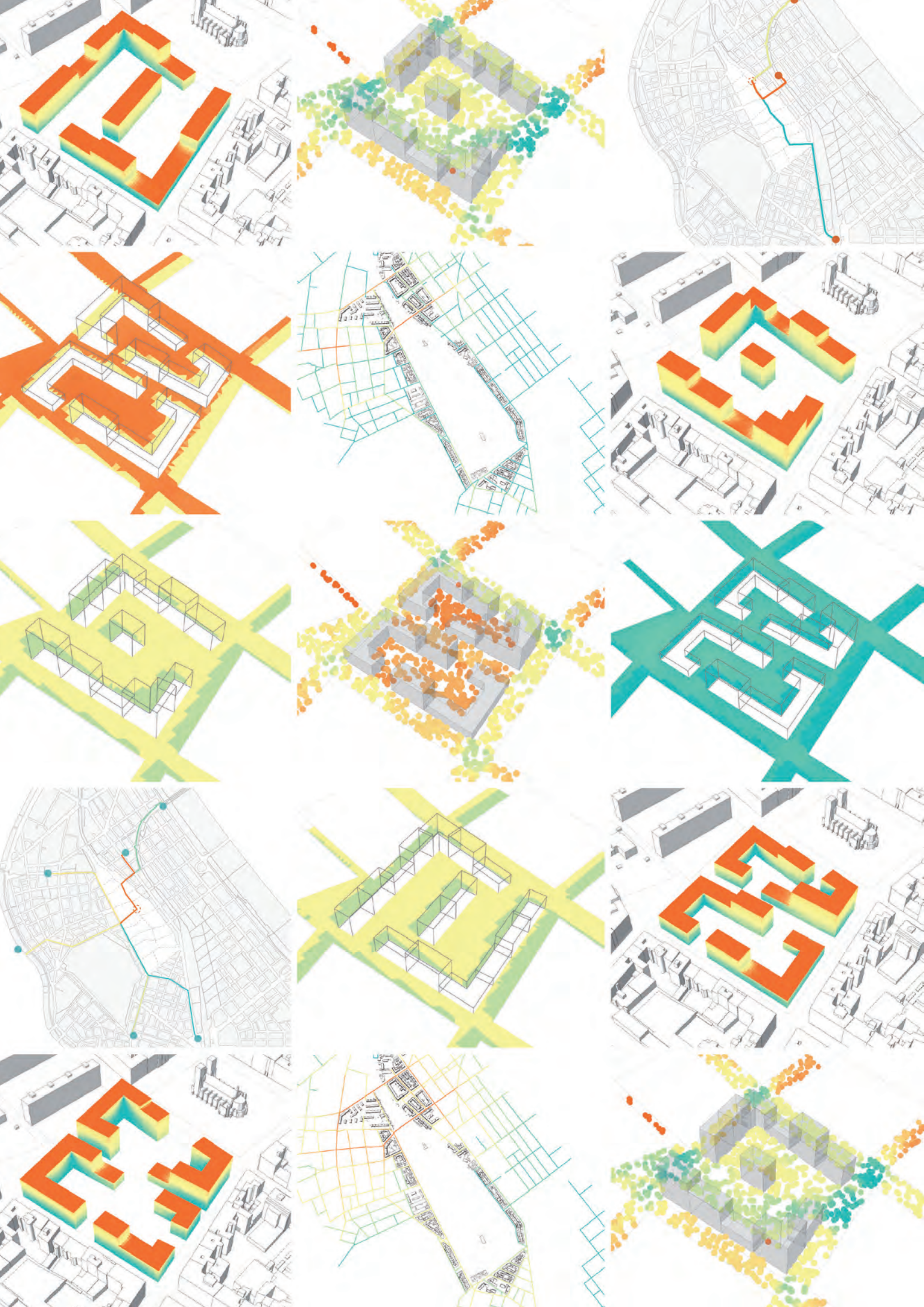
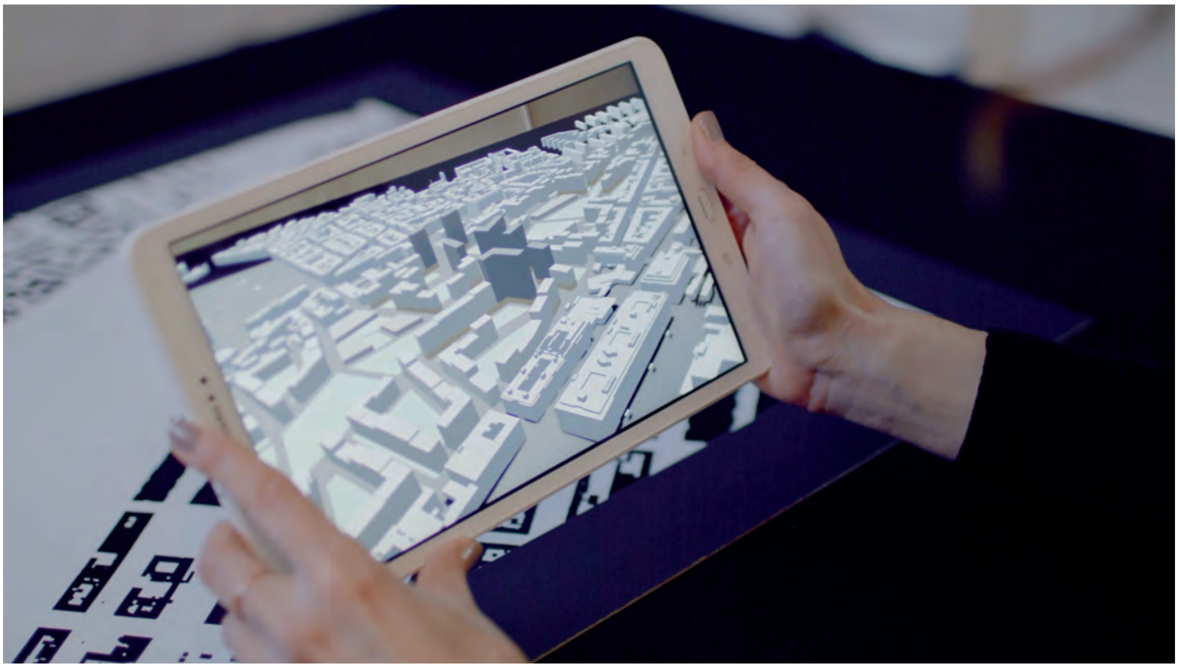


Figure 40
Analyses and simulation results on visibility, microclimate, solar radiation and visual integration

The generation of design options leads to a high number of performance results. This demand for an intelligent design space exploration runs simultaneously with the design process in order to sort, quantify and select the best scenarios [7]. The results can be integrated into interactive online mapping and Augmented Reality (AR) presentation in order to facilitate further discussion between team members, stakeholders, clients and inhabitants (see Figure 41). The intent of applying semi-automated, digital tools within this process is to assist the designer intelligently. The potential to create a sustainable environment through integrative procedural urban planning is promising since this workflow allows the further incorporation of additional analyses and simulation.

Figure 41
Augmented reality visualisation of a masterplan. Copyright Photograph Art-Media



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SOUTH CRESCENT

CARBON & ECOLOGY
WITHIN THE DESIGN PROCESS
Environmental Impact Assessment

Edited by

Lisanne Havinga
Catherine De Wolf
Antonino Marvuglia
Emanuele Naboni

Chapter Cover Image - The Circular Building

The Circular Building at the London Design Festival 2016, developed by Arup, aimed at showcasing the implementation of circular economy principles in practice. The building was designed and constructed for all building components to be disassembled and reused. Digital tools in the forms of component 'tags' linked to an online database and BIM-system were implemented. This indicates a strong link between a circular economy approach and data-driven technologies

Courtesy © Arup

CARBON AND ECOLOGY WITHIN THE DESIGN PROCESS

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TOWARDS A CIRCULAR BUILT ENVIRONMENT

Lisanne Havinga *Eindhoven University of Technology (TU/e), the Netherlands*
Catherine De Wolf *École Polytechnique Fédérale de Lausanne (EPFL), Switzerland*
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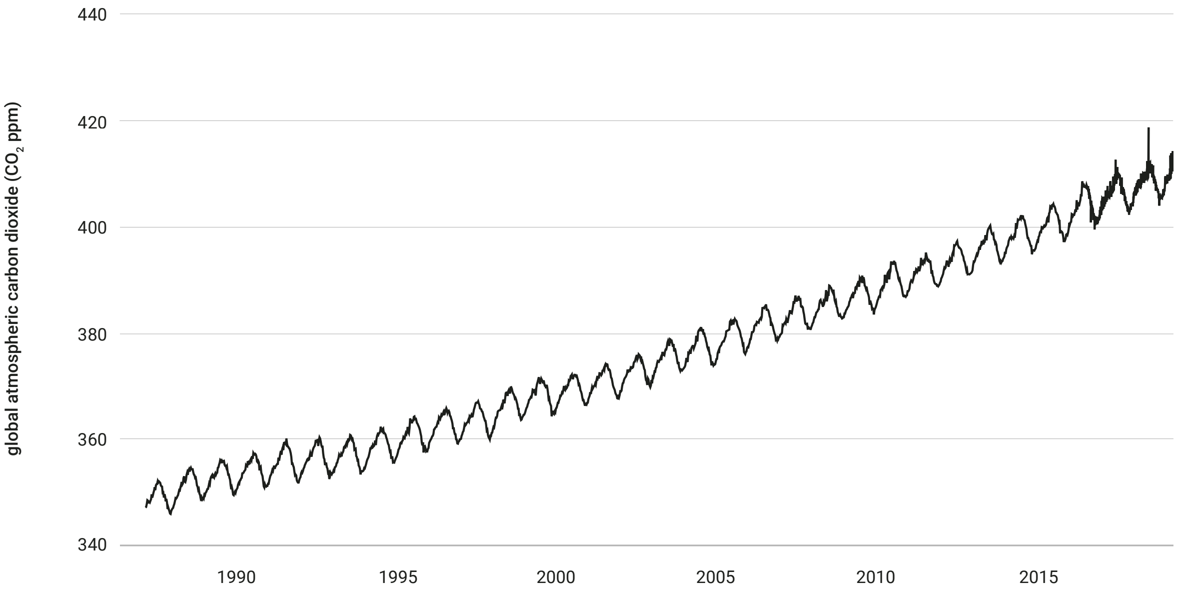
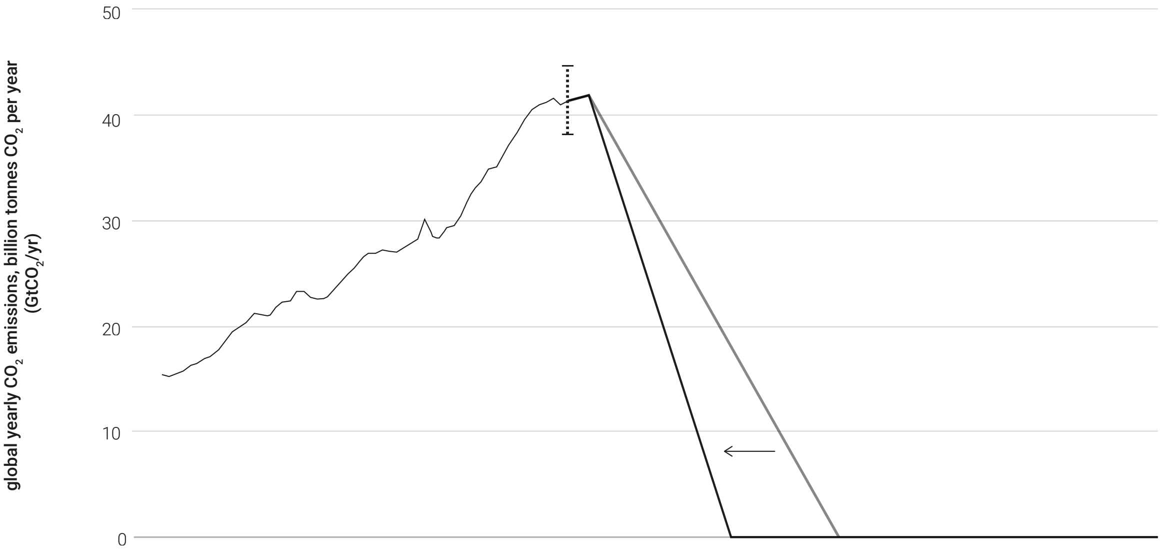
Despite the increasing awareness surrounding climate change, since the release of the Brundtland report in 1987, the global atmospheric carbon dioxide concentrations have continued to steadily increase (see Figure 1). At the same time, the recent IPCC report indicates that human activities are today estimated to have caused approximately 1.0°C of global warming above pre-industrial levels and that impacts from global warming on land and ocean ecosystems have already been observed. The report prescribes a 'carbon budget' as a simplified way of representing the maximum additional carbon dioxide (CO_2) emissions that can enter the atmosphere to limit global warming to 1.5°C. The remaining carbon budget is estimated at 420 $GtCO_2$ for a two-thirds chance (and 580 $GtCO_2$ for a fifty-fifty chance) of limiting warming to 1.5°C. With current emissions of approximately 42 $GtCO_2$, this is the equivalent of 10 years (and 14 years) of current emissions. The rapid CO_2 reduction necessary to potentially limit global warming below 1.5°C is shown in Figure 2. This chapter focuses on two key aspects: the implementation of the circular economy in the construction sector, and the measurement and reduction of environmental impacts, including global warming potential. These notions are strongly related to the UN's Sustainable Development Goals (UN SDG's), the most closely linked are:

- UN SDG #11: Sustainable Cities and Communities: Make cities inclusive, safe, resilient and sustainable
- UN SDG #12, Responsible Production and Consumption: Ensure sustainable consumption and production patterns
- UN SDG #13, Climate Action, Take urgent action to combat climate change and its impacts


global atmospheric carbon dioxide (CO_2 ppm)
440
420
400
380
360
340
1990
1995
2000
2005
2010
2015


global yearly CO_2 emissions, billion tonnes CO_2 per year ($GtCO_2$/yr)
50
40
30
20
10
0
1960
1980
2000
2020
2040
2060
2080
2100

FROM A LINEAR TO A CIRCULAR ECONOMY

In the EU, the use and construction of buildings are responsible for approximately 40% of final energy consumption [1], more than a third of CO_2 emissions [2], a third of water consumption [3], more than half of all extracted materials [4], and a third of waste production [5]. Today, the construction industry still mainly operates within a linear economy: materials are extracted, used and finally disposed of as waste. In order to address climate change and other environmental impacts, the notion of a circular economy has gained increasing attention worldwide as being a comprehensive concept at the forefront of sustainability thinking, which provides an alternative to a traditional *'take-make-dispose'* linear economy. A leading think-tank, The Ellen MacArthur Foundation, has catalysed recent momentum for the topic, and defines it as an *'industrial system that is regenerative and restorative by design, rethinks products and services to design out waste and negative impacts, and builds economic, social and natural capital'* [6]. A circular economy (CE) aims to extend the lifetime of materials and products to keep products, components, and materials at their highest utility and value at all times. The value is maintained or extracted through an extension of product lifetimes by reuse, refurbishment, and remanufacturing, as well as the closing of resource cycles—through recycling and related strategies [7].

Figure 1

Atmospheric CO_2 concentrations (ppm) derived from in situ air measurements (Mauna Loa, Observatory, Hawaii), from the release of the Brundtland Report 'Our Common Future' in 1987, until 2019 (Datasource: Scripps Institution of Oceanography)

The concept of the CE can be traced back to a multitude of historical antecedents and not to a single author [7]–[9]. As such, the concept has gained momentum since the 1970s and has been refined and developed in various schools of thought, which will briefly be introduced. Walter Stahel, and Genevieve Reday in their 1976 research report to the European Commission entitled *'The Potential for Substituting Manpower for Energy'* [10], described an economy of closed loops and its positive effects in terms of both job creation and economic competitiveness as well as reduction of resource use and waste. Stahel is also credited with having coined the expression *'Cradle to Cradle'* in the late 1970s, and with identifying a *'functional service economy'*, focussed on selling utilization and services instead of products and goods as the ultimate sustainable business model of a loop economy in his 1981 paper '*The Product-Life Factor'* [11].

Figure 2

Stylised net global CO_2 emission decline from 2020 to reach net zero in 2055 or 2040, corresponding to fifty-fifty (light grey) and two-thirds (dark grey) probability of limiting global warming to 1.5°C (Adapted from Source: IPCC report 2018, SPM1)

At the same time, in the 1970s US landscape architect John T. Lyle pioneered the term *'regenerative design'*, which had already been formulated earlier by Robert Rodale for agriculture [12]. In his book entitled *'Regenerative Design for Sustainable Development'* [13], Lyle states *'A regenerative system provides for continuous replacement, through its functional processes, of the energy and* *materials used in its operation'*.

Building on both Stahel and Lyle's ideas, Michael Braungart and William McDonough (who had collaborated with Lyle) established the product and system certification Cradle to Cradle [14] (a coinage of Stahel's), which treats industrial flows as metabolic and waste as nutrients, of which there are two main categories: technical and biological.

The field of industrial ecology (IE) is also strongly linked to the circular economy. Frosch and Gallopolous [15], with the publication of 'Strategies for Manufacturing', marked the beginning of industrial ecology (IE) as a research field. As pointed out by Blomsma & Brennan [8] and Lifset and Graedel [16], IE has manifested itself in two distinct areas. Firstly, IE focusses on the systematic analysis of resource flows. As such, it has worked to provide systematic evaluations of environmental impact using such tools as life cycle assessment (LCA) and has been quantifying the flow of materials and energy in industries, supply chains, facilities, cities, nations, and the globe [7]. Secondly, IE has studied eco-design, looking to non-human 'natural' ecosystems as models for industrial activity, often referred to as *'biological analogy'* [16].

Both the concepts of regenerative design and cradle to cradle also include notions of biological analogies of nature or *'nature-inspired design'*. This relates to the concept of biomimicry, which is defined as *'a new discipline that studies nature's best ideas and then imitates these designs and processes to solve human* problems' by Janine Benyus, in 'Biomimicry: Innovation Inspired by Nature' [17]. Other concepts and publications that are strongly related to the development of the notion of the circular economy include: Boulding's essay on *'The Economics of the Coming Spaceship Earth'* [18], Commoner's *'Four Laws of Ecology'* [19], '*Natural Capitalism'* [20], and '*the Blue Economy'* [21].

Because of this rich history of the development of the concept, and the many aspects that have become associated with the concept, the CE is today often seen as an *'umbrella concept'* [8], [22], [23]. The CE feeds from multiple, rich sources [22] that are not new individually, but through CE are framed in a new way by *'drawing attention to their capacity of prolonging resource use as well as to the relationship between these strategies'* [8]. The concept is still in the process of being further developed, which can be seen in the changing and blurry boundaries, and as such cannot be pinned down to an absolute definition or truth.

Blomsma and Brennan [8] provide an overview of several interpretations of what a circular economy could or should look like according to different actors, and conclude that the various strategies '*predominantly and increasingly seek to extend resource life, for example: reuse, recycling, remanufacturing, servitization, repair, waste-to-energy, product longevity approaches, and the cascading of substances (i.e., the transformation of materials through various use phases)*'.

CIRCULAR ECONOMY IN THE CONSTRUCTION SECTOR

Although the implementation of circular economy principles in the construction sector is rapidly gaining momentum, this is still mostly related to innovative 'prototype'-like projects. Some examples include the Circular Building and the People's Pavilion by Arup, presented at the London Design Festival and the Dutch Design Week (see chapter cover and the introduction of the chapter titled 'Case Studies Showcasing Regenerative Design' for more information). Other examples include innovative business models for leasing façade systems or other building components.

In the construction sector, circular practices tend to occur at the material or component level. They include design for disassembly, material and component reuse and recycling, selective demolition, and designing out waste. Recovering materials from existing buildings to reduce the extraction of raw materials falls within the concept of urban mining, and in this context, the existing building stock is sometimes referred to as a 'material bank'. To use existing buildings as material banks, several actions need to be undertaken.

First, information about the building components and the materials used need to be collected. In this respect, 3D scanning surveys can help in creating BIM models and in populating them with information that is possible to collect on site. For a building that is meant to be demolished, a pre-demolition audit can be conducted to collect the necessary information. Pre-demolition audits are detailed records of the elements (material, quantities, dimensions, possible treatment path) that can be used to plan and optimise deconstruction.

Second, to dispose of materials at the end of their service life or to foresee their reuse, selective deconstruction of the building elements needs to be carried out. Currently, there is no operational model available to certify the quality and safety of these secondary materials and to ensure their placement on the market. Also, if the secondary materials find a place in the market, after their careful deconstruction, they need to be cleaned, often repaired, packed, transported, documented, stored and sold.

Selective deconstruction for reuse is an option that needs to be assessed at least according to economic (the price of new materials compared to the cost of reusing materials), technical (mechanical and esthetical properties, ease of disassembly, etc.) and environmental (the emissions of new materials compared to reuse/recycling materials) criteria.

It is important to remember that above all, a circular economy aims to extend the lifetime(s) of products and materials. As such, although the circular economy is mostly translated to notions of reuse and recycling, it is important to also take into account the durability and longevity of a product or a buildings' lifetime. Although the Pantheon in Rome was not designed to be disassembled or recycled, the materials and products used in its construction have been functioning for over 2000 years. As such, the adaptive reuse of existing buildings or the design of buildings with the flexibility to adapt to future needs can also contribute to the goals of a circular economy.

LIFE CYCLE ASSESSMENT

As introduced, the circular economy concept is closely linked to the field of industrial ecology, which studies the flows of material energy. As part of this field, Life Cycle Assessment (LCA) is developed as a means to assess the emissions and associated environmental impacts occurring throughout a products' life. As such, LCA can be used by designers to assess and improve the circularity and the environmental impacts of their building projects. As regenerative design aims to eliminate negative impacts, and create buildings that have a positive impact on the environment, LCA can be used to evaluate the extent to which this is achieved. For example, to evaluate the Global Warming Potential, LCA can be used to assess the overall green house gas emissions occurring throughout a buildings' lifetime, and translate those to an overall kg CO_2 equivalent. In addition to global warming, the acidification potential, eutrophication potential and ozone depletion potential are assessed as part of the European guidelines (EN 15978). This chapter explores LCA-based methods that can support the built environment industry to design, evaluate, and apply circular economy principles correctly.

Up to now, LCA for buildings has not been widely applied because of its complexity and time-consuming nature. Several studies have been trying to address this issue through the use of parametric tools and building information modelling (BIM), which enable them to implement circular design principles. Parametric tools indeed increase productivity by allowing building designers to automatically generate geometric compositions based on, for example, circular design parameters. BIM models enable different stakeholders to communicate information about material quantities and specifications, essential to implement a circular economy, for instance, through material passports. These tools were initially designed for optimising the design and construction phases in order to achieve reduced impacts, but over the years they have been used to support the required data and features that are needed for the implementation of a circular economy. Visual programming language software tools include geometric modelling and scripting functionalities, leading to a high potential for designing with reused components from an available building stock, for example.

TOOLS TO IMPLEMENT CIRCULAR ECONOMY AND LIFE CYCLE ASSESSMENT

This chapter presents an overview of the current tools and processes used to assess the environmental impact of the built environment. The implementation of circular economy principles in these assessments is also addressed. These digital tools and approaches can be used to reduce the environmental impact of buildings and move towards buildings that have a positive impact on the environment, building meeting regenerative design targets. As such, the integration of LCA in the design process is described, which – although gaining momentum and starting to be implemented in certification schemes – is far from standard practice. This integration is described from multiple perspectives, ranging from large scale urban LCA's, to parametric building LCA's and explorations of the sensitivity of LCA considerations.

Panu Pasanen and Rodrigo Castro discuss the importance of reducing embodied carbon. They discuss the digital tools that can be adopted to assist developers and designers in attaining this goal. In addition, they discuss the necessity of implementing more stringent regulations and standards when it comes to addressing embodied carbon.

Catherine De Wolf discusses the potential of reusing building structures to meet regenerative targets. She frames this discussion within the notion of environmental impact assessment, indicating that no consensus exists on how such circular economy principles should be integrated in LCA.

Antonino Marvuglia notes that while most research into LCA is still focussing on product or building level, literature applying LCA at an urban, regional or district scale remains scarce. Subsequently, he presents a digital workflow to conduct life cycle assessment at an urban scale by means of coupling the LCA model to a Geographic Information System (GIS) model. The lessons learnt from the application of this methodology in a recent research project are elaborated.

Alexander Hollberg, Kristoffer Negendahl and Mateusz Szymon Płoszaj-Mazurek all focus on the combination of parametric modelling and LCA. Alexander Hollberg introduces the key principles of parametric LCA, it's importance to be implemented as part of the early design stage, and present an easy-to-use software tool integrated in Sketchup and Rhinoceros. Kristoffer Negendahl describes the experiences of a research project in which five architectural design studios experimented with implementing LCA as an important driver of design decisions. His reflections are insightful yet at times critical, and identify some of the challenges that need to be overcome in implementing LCA in everyday architectural practice. Mateusz Szymon Ploszaj-Mazurak presents an example of a parametric optimisation of a multifamily building in Poland, aimed at defining the optimal building geometry by varying eleven different parameters and applying a genetic algorithm to reduce simulation times.

Andrea Meneghelli, Kasimir Forth and Tiziano Dalla Mora and Fabio Peron discuss the integration of LCA in Building Information Models (BIM). Andrea Meneghelli conducted a sensitivity analysis of some of the most common assumptions made in LCA, being the percentage recycled content of metal materials, wastage during construction, transportation distance from manufacture to site, and embodied carbon coefficient for freight transportation. Kasimir Forth discusses the challenge of achieving a fully automated BIM to LCA process. He identifies the flaws in current automated workflows, and proposes an optimised workflow. Tiziano Dalla Mora conducts a hands on evaluation of two LCA tools with BIM integration. The evaluation discusses the available EPD databases, the interoperability with BIM software, the workflow, and the way the tools report the outcomes of the assessment.

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REDUCING EMBODIED CARBON: REGULATIONS AND TOOLS

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The rapid growth of global urban populations is set to double the size of the global building stock in the next 40 years [1]. This generates an unprecedented demand for construction and required construction materials. The greenhouse gas emissions from the manufacturing of these materials are emitted even before project completion, which makes embodied carbon reduction essential. The carbon impact of the required new construction has been estimated at over 100 gigatons of CO_2-eq [2,3]. Actions to reduce the embodied carbon include the reduction of raw material extraction, promotion of the use of low-carbon alternatives, and an increase in the reuse of material.

In a business-as-usual scenario, *cumulative operational carbon* will, in time overtake the initial impact of *embodied carbon* as well as the accumulated impacts from *refurbishment*. However, when we consider decarbonisation of the energy grid, the accumulated emissions from operational energy use remain below the embodied carbon of the growing building stock for the same period.

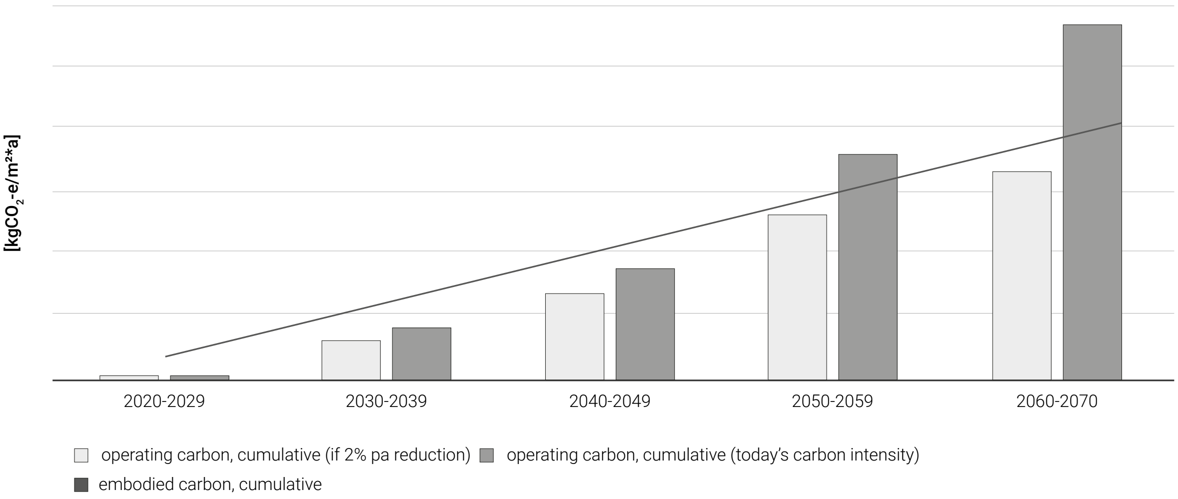


Figure 3
Embodied and operational carbon scenarios for new buildings 2020-2070 [2]

To illustrate this point, Figure 3 shows the comparative impact of the *embodied carbon* (line) and the two *operational carbon* scenarios described above (grey bars) between 2020 to 2070. This assumes a steady growth in the new building stock. Embodied carbon is assumed to be one-fifth of life-cycle emissions, and it grows in proportion to the building stock. The operating carbon is shown with two scenarios; one with an annual 2% decarbonisation and another one with business-as-usual carbon intensity. Embodied carbon, unlike operating carbon, cannot be reduced effectively by decarbonisation of grid electricity, and this embodied carbon is, unfortunately, the leading long-term cause of emissions for new construction.

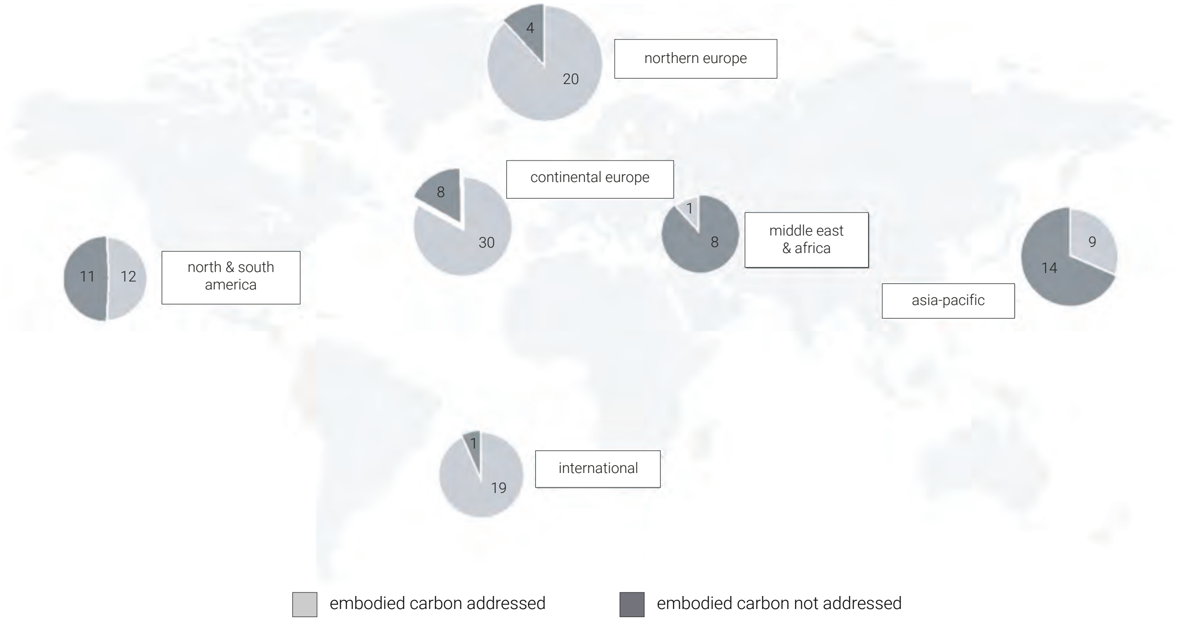
The scale of the required undertaking is to reduce the embodied carbon from all the world's new construction – estimated at 230.000 million m^2 by 2060 [1]. However, review of building mass in large metropolises suggests that a small fraction, approximately 3%, of the buildings represent one half of the total built area [4]. Starting with these large buildings is the obvious first step.

By now, it is clear that achieving a sizeable reduction in the embodied carbon of new construction globally requires stable business drivers for the constructors and very high cost-efficiency for sustainable design and construction. This section will look at each of these, starting with the business drivers.

CREATING A BUSINESS IMPERATIVE FOR DECARBONISATION WITH REGULATIONS, POLICIES AND CERTIFICATIONS

The Embodied Carbon Review [2] found that the number of regulations, certifications and standards addressing embodied carbon in construction has doubled in the last five years, reaching a total of 105 such systems. At the same time, one-third of all identified green building systems do not yet address embodied carbon. Despite this very positive development, the vast majority of current construction projects are not applying any of these carbon reduction frameworks. Figure 4 shows the ratio of systems addressing and ignoring embodied carbon by region [2].

The vast majority (86 %) of identified green building systems are voluntary certifications, guidelines or standards, with one-seventh being regulations (14 %). When enforced, regulations can cover all targeted new construction in the regulated area. This makes the regulatory route the most promising tool for achieving carbon reductions, which is likely also the main reason why several governments – many of them in Europe and North America - have started preparing regulations.



However, over 80 % of the new buildings will be built in Asia, the Middle East, Africa and Latin America. Much of this growth is happening in megacities in developing countries. These megacities may have resources comparable to smaller countries with which to develop, deliver and enforce environmental regulations on new construction.

As cities in many cases have the zoning monopoly and control the development of land resources and incentives related to these processes, they are particularly well placed to implement binding regulations and suitable voluntary incentives for the local businesses to respond to. For example, the Zero Cities pilot project aims at helping cities develop a policy roadmap to achieve a zero-carbon building sector [5]. These carbon reduction policies can benefit the local economy as the use of local products causes less transport-related greenhouse gas emissions. Also, more carbon efficient construction will lead to less health-damaging emissions from both manufacturing and construction processes.

Some regulations also target refurbishment of the existing and ageing building stock with the intent of reducing operational energy consumption. Such upgrades also lead to the incorporation of new systems and materials to the building, and waste flows from used materials, which contain embodied carbon emissions. It is possible to optimise this kind of renovation for carbon and life-cycle cost reductions.

Figure 4

Prevalence of embodied carbon evaluation in green construction systems [2]

Also, by understanding the embodied carbon of materials in buildings, it is possible to include material recovery and reuse in strategies to help reduce the extraction of raw materials and preserve the value of existing ones.

DIGITAL TOOLS ARE REQUIRED FOR COST-EFFICIENCY AND QUALITY TO MAKE EMBODIED CARBON MAINSTREAM

Carbon-conscious design or specification of sustainable materials are not yet mainstream skills for the design community. Often, these services are secured in the form of external expertise. As introduced, about 3% of the buildings represent one half of the total built area in metropolises and provide a great opportunity to concentrate efforts. Even these projects would require at least tens of thousands of such experts [4]. The associated resource and cost constraints limit the feasibility of using external expertise in all projects. Therefore, an approach allowing the principal designers to improve project sustainability is needed.

This competence gap is compounded by the perceived and partly factual complexity of the most common method for embodied carbon quantification – Life Cycle Assessment (LCA). As a science-based method, it includes concepts, processes and definitions foreign to typical building design teams. Simplifying carbon quantification sufficiently to make it applicable by design teams is a precondition to measure the effectiveness of any embodied carbon reduction policy.

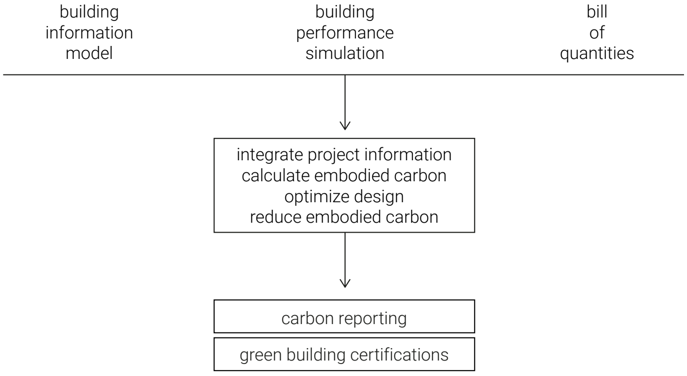


Figure 5

Multiple data sources used to automate whole building LCA

To this end, digital design tools like Building Information Models (BIM) are already used to manage the complexity, changes, and coordination in building projects. Also, BIM has been piloted for the verification of regulatory compliance by some cities, allowing for the enforcement of policies and requirements. Also, as repositories of building life cycle data, digital design tools can be used to calculate environmental performance and material flow linked to the building's refurbishment [6]. This is possible thanks to the capability in BIM to enable quick material quantity take-offs at any stage of the design process. Consequently, this data extraction with an efficient calculation engine can help automate the LCA process and provide relevant and timely feedback to the design team. This automation process is presented in Figure 5.

Similarly, building energy models (BEM) or building performance simulation (BPS) are simplified building models used to simulate the thermal exchange between the inside and outside of buildings, its lighting requirements, and allow the user to estimate the energy demands or the building energy performance. An important part of the modelling process includes the definition of materials in the building envelope that drive its thermal performance. Again, this information can be accessed to produce reliable LCA and embodied carbon calculations. Therefore, both BIM and BEM/BPS can effectively support the automation of embodied carbon calculations and thereby help to improve building design in an integrated way.

TESTING THE PROMISE OF DIGITAL TOOLS IN PRACTICE – AN END-TO-END PROCESS WITH DATA FROM REAL-LIFE PROJECTS

To deliver on the promise of the efficiency of BIM-automation for carbon accounting, all the steps from data collection, embodied carbon calculation and result reporting have to work seamlessly. The essential omission from the present automation toolchain is a method to ensure the quality of results. Otherwise, this will simply generate work for the modellers, at least until practices are standardised. A Model Checking approach was tested in research funded by the Finnish KIRA-Digi program. The tests were conducted using One Click LCA, a cloud-based, easy to use LCA software. One Click LCA has nine different BIM integrations in place and is also used in the Southern Hemisphere [7].

The project tested 61 BIM models in IFC format from 10 countries. All models were created for design purposes without consideration for the use of LCA. In the project, a Model Checker module was developed and integrated into the One Click LCA software to review the geometrical definitions. The BIM models were imported to One Click LCA for an automated LCA and related quality analysis. The Model Checker proved to work and was able to report on the suitability of the data for LCA. This was completed with an LCA Checker tool that verifies if the BIM was likely to have missed information or to have gaps compared to the required scope of the LCA [8].

This project proved that digital design tools can deliver required productivity gains and that LCA automation from BIM models works in practice, even when projects are not specifically prepared for that. Its practical value was validated in a follow-up user research in which 93 % of the users who had used the Model Checker rated it either very useful or useful for their work [9]. While digital design tools can provide productivity gains, significant developments in policy, regulations or competence and standards are required to create business drivers that stimulate the use of these tools in order to make embodied carbon reduction the norm in new construction wherever possible.

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THE REUSE OF BUILDING STRUCTURES IN LCA

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In structural design, different milestones exist in the march towards regenerative design. The first step is achieving sustainable structures, which would reduce the impact on the environment. Current efforts are evaluating where we are on the achievement of sustainable structures, such as the Carbon Leadership Forum's work on benchmarking and reducing embodied carbon. To this end, a database was developed to collect structural material quantities of existing building structures (available at deqo.mit.edu), which shows that there is still much room for improvement to reach the goal of zero carbon structural design by 2050 (Structural Engineers 2050 Commitment). Load-bearing structures constitute both the most material weight and the highest embodied carbon emissions in buildings. The second step is achieving restorative structures, which means that we not only achieve zero carbon structures but also contribute to reversing the harm already done to the environment.

The ultimate goal is to reach regenerative structural design, which would improve the eco-system both in terms of environmental impact and socio-economic well-being. While it is not yet clear how our building structures can truly be regenerative, a circular economy is one tangible means to achieve it. The key question is: how can we integrate a circular economy into current life cycle assessment (LCA) tools when evaluating structural design projects?

LCA TOOLS & CIRCULAR ECONOMY

In a circular economy, the maximum value is extracted from goods by keeping them in use for as long as possible while minimising their environmental impact and by turning them into resources for others after their service life. While recycling is common practice in the current linear economy, it often uses energy (e.g. for melting steel) or downgrades materials (e.g. concrete crushing for road construction or making chips from wood). In a circular economy, the optimal approach is to make lighter products that last longer and can be reused; recycling only makes sense as a material management strategy when this is not possible.

Figure 6
London Stadium (Courtesy: Populous)

Because a circular economy in structural design implies reusing structural elements over multiple life cycles of multiple buildings, current LCA tools – which measure the impacts of one product over one life cycle only – are not able to quantify the benefits of reusing components. This would require predicting how many life cycles a product will last. If the regenerative design is indeed to be achieved, the environmental impacts of the building structure need to be reduced if not annihilated or reversed. Reusing existing structural elements that would otherwise go to landfill or recycling facilities is the first step. Examples include the London Stadium (Figure 6), which reused excess steel from a nearby gas pipeline and can be partially disassembled for downsizing the stadium after the games, and the Circular House, in which the steel elements were leased from the material manufacturer and are to be reused again in other projects after the dismantling.

LIFE CYCLE STAGES IN A LINEAR VERSUS CIRCULAR ECONOMY; THE BOUNDARIES OF LCA

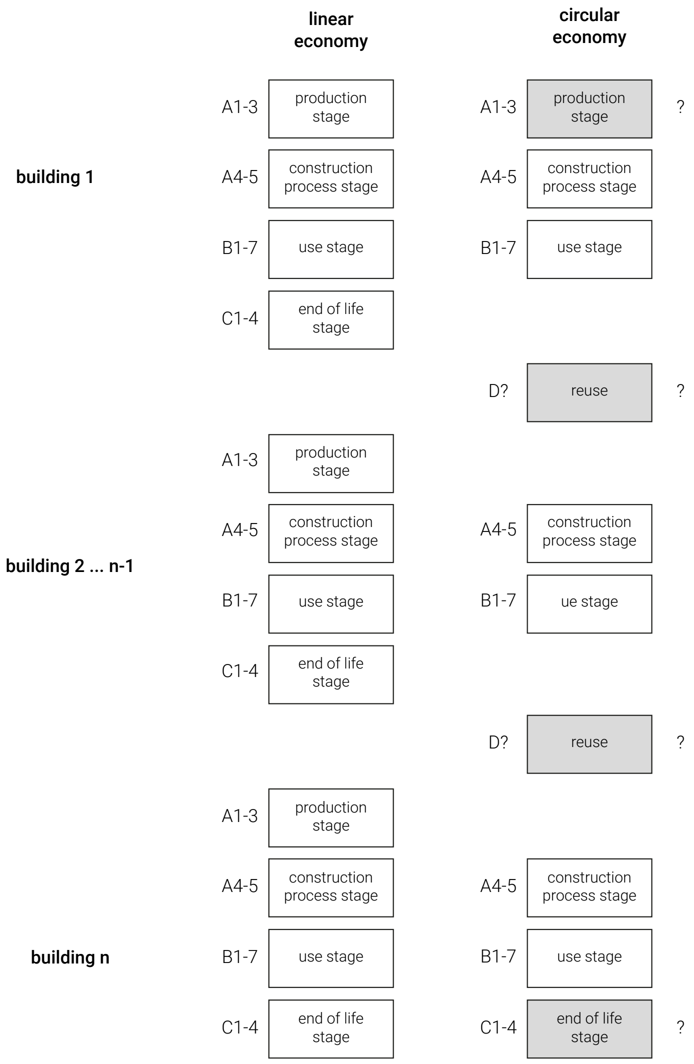
The construction industry uses several tools to optimise their structures and assess the environmental performance of building structures. Current LCA tools are used to evaluate environmental impacts, such as global warming potential (GWP), ozone layer depletion, smog creation, acidification, eutrophication, etc. LCA tools have specific boundaries (for example from the production of new building materials to the demolition of the building). Moreover, to describe the impacts, LCA tools must use a functional unit as a common denominator, such as measuring the gross floor area of buildings, to normalise the results. While most structural elements are produced for specific building use and life cycle, a circular economy approach would extend the use of these elements over multiple life cycles of multiple buildings.

At the time of construction, a conventional building element may have a lower initial environmental impact or cost per m^2 than its reversible counterpart. However, when the conventional building is demolished, its materials and elements cannot easily be disassembled and are often landfilled. In contrast, for the reversible building, the materials can be reused instead of landfilled, making the environmental impact per m^2 per year of use of these materials much lower. An LCA tool should, therefore, take into account the multiple life cycles of the reversible building element, showing its potential over different life span scenarios. Current LCA tools only include the EN 15978 life cycle stages of one building life cycle: production (A1 to A3) stage, construction process (A4 to A5) stage, use (B1 to B7) stage, end-of-life (C1 to C4) stage, and beyond (D). Module D, which includes the benefits and loads of reuse, recovery, and recycling potential, is rarely considered. Indeed, no consensus exists on which product life cycle these benefits and loads are allocated to, as denoted by the question marks in Figure 7.

Current methods to evaluate the emissions savings of reuse include deducting relevant impacts in the production stage when reused elements are used, as well as in the end-of-life stage when the waste elements will be reused rather than transported to a landfill site. These methods raise the question of double counting and allocation: are the saved emissions due to reuse deducted from the LCA results of the building being disassembled or from those of the new building in which the components will be reused? Are all production stage emissions accounted for in the first building life cycle, or are they distributed over all the building life cycles until the material is demolished?

Figure 7

Life cycle stages in a linear versus circular economy: which building benefits from the emission savings of reuse? (Source: Adapted from [9])


linear economy
circular economy
building 1
A1-3
production stage
A1-3
production stage
?
A4-5
construction process stage
A4-5
construction process stage
B1-7
use stage
B1-7
use stage
C1-4
end of life stage
D?
reuse
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building 2 ... n-1
A1-3
production stage
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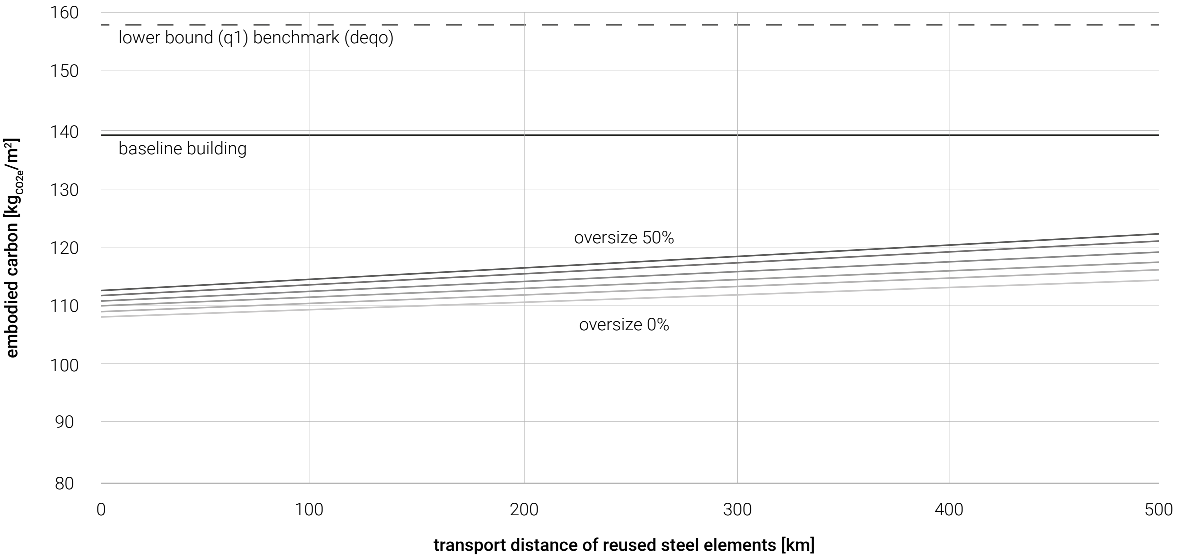

Figure 8

Parametric assessment of reuse for different transport distances and oversize percentages (Source: Adapted from [10])

LCA IN DESIGN

LCA is Often used at the end of the design stage when much information on the material quantities and choices is available, but when possible steps towards lowering the environmental impact of building structures are limited. It is far more useful to integrate LCA in the early stages of the design process. Parametric design with direct feedback on the LCA results of design choices has the potential to enable this early design integration: the designers can check the influence of various parameters on the environmental impact of their project. Parametric design, combined with Building Information Models (BIM), can help the architect to optimise projects during the design process: the data of multiple collaborators and existing databases can be used at different stages. The architect or structural engineer can vary the parameters while getting direct feedback from the LCA of the BIM model to understand the impacts of design decisions.

For example, because a building's structural elements need to be transported over various distances to be reused (compared to locally available new materials), and because the elements might have to be oversized when the required cross-sections cannot be found among the currently available stock of elements, embodied carbon emissions of reused elements can vary. As an example, Figure 8 represents a parametric analysis comparing the embodied carbon of a newly constructed baseline steel office building (140 kg CO_{2e}/m^2), with a range of results using reused steel elements for the same building: the case study on reused steel has a smaller GWP compared to the baseline new construction, up to an oversize of 25% and transport distances of 2000 km.

STRUCTURES & REGENERATIVE DESIGN

Although current efforts aim to achieve zero carbon structures, these structures cannot be dematerialised entirely, as a minimum amount of structural materials is still needed in the building. Therefore, to avoid any environmental impacts related to the extraction of raw materials or to the energy needed for recycling existing materials, the reuse of structural components is an obvious choice. This reuse allows the structure to become 'nearly zero carbon'. What we have learned is that circular economy principles alone will not make structures regenerative, but they are nonetheless a prerequisite for regenerative design, which remains an enormous challenge. Given that the structure is a part of a building, a combined approach is essential: using no raw materials and allowing the building to regenerate so that social and ecological homeostasis is truly achieved.

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LCA AND GIS FOR URBAN IMPACT ASSESSMENT

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An assessment of the global (environmental, economic and social) sustainability performances of cities is needed for decision-making support in sustainable urban planning and responsible policymaking. For this purpose, a holistic evaluation based on internationally recognised methods, such as a Life Cycle Sustainability Assessment (LCSA), is a suitable approach to address trade-offs between life cycle stages, as well as between the different sustainability pillars. In the context of the built environment, awareness of these challenges has spurred the consolidation of the known concepts of a building sustainability assessment and the proliferation of new design concepts based on regenerative design. This brings about several conceptual and practical elements that have started to be addressed in the literature but go beyond the focus of this short contribution, which will only focus on the environmental assessment component of urban sustainability, and in particular, on the evaluation of the aspects related to the building stock. In this context, the contribution addresses the advantages and challenges related to the integration of Geographical Information Systems (GIS) in Life Cycle Assessment (LCA) study at the urban scale. The currently existing different levels of this integration are discussed below.

COUPLING GEOGRAPHICAL INFORMATION SYSTEMS (GIS) AND LIFE CYCLE ASSESSMENT (LCA) AT THE URBAN SCALE

Cities are responsible for 75% of global energy consumption and about 70% of global greenhouse gas emissions [1]. In 2017, more than 74% of the European population lived in cities, and recent projections indicate that by 2050 this percentage will rise to almost 84% in Europe, while at the global level, it will be close to 68%. Building stock modelling is one of the fundamental modelling blocks in the sustainability assessment of cities. While bottom-up building stock models up to the last decade mainly focused on operational energy use, the focus has now definitely shifted from the use phase to the entire life cycle.

More recently, the interest of researchers has moved from studying individual buildings to considering stocks of buildings and larger systems, such as cities or neighbourhoods [2]. Notwithstanding this clear tendency, which mirrors a globally recognised research need, the LCA literature is still scarce at the neighbourhood and city level and is highly influenced by the complexity of the task (due to several existing methodological and operational challenges), and the dependency of the systems studied on the local context. This leads to heterogeneous approaches in LCA modelling at the urban scale.

In computer science jargon, 'coupling' describes an automatic exchange of information between software components. The coupling of GIS and LCA can significantly facilitate the task of managing and processing spatially distributed information at large scales, achieving a higher level of detail [3]. GIS is particularly promising to localise impact sources and provide spatialized input data, develop spatialized inventory models, and visualise results for stakeholders (creating spatial maps of the environmental impacts, as well as of any other decisional indicator derived from this).

Three levels of coupling between GIS and LCA can be identified in the literature: (i) no coupling, (ii) soft coupling, and (iii) hard coupling [3]. The level of interdependence, coordination of the information between the two components and directionality of the information flow reach a higher degree of completeness and complexity when passing from type (i) to type (iii) (Figure 9). In type (i) models, the two components do not exchange any information; in this case, GIS is used almost exclusively to visualise the Life Cycle Inventory (LCI) data. In type (ii) models, GIS is used to perform an automated treatment of spatial data and generate new inventory data that will be used by LCA or to perform advanced simulations, such as running spatial optimisation models [4].

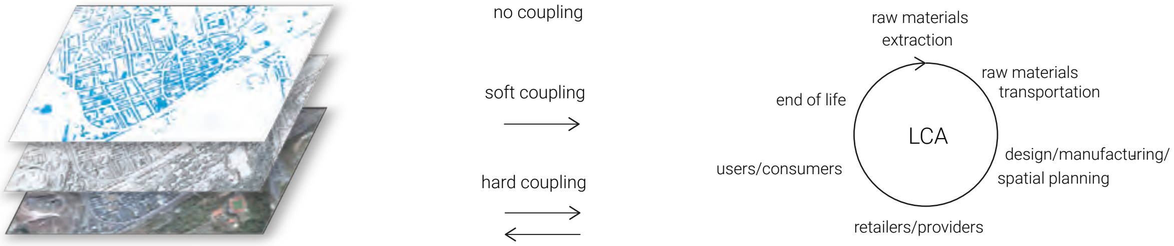

Figure 9

Levels of possible coupling between GIS and LCA. The level of interdependence and coordination of the coupled modules and the volume of information transmitted between the modules increases when passing from 'no coupling' to 'hard coupling'

Once the new information is produced and fed to the piece of software used to perform the LCA (called *LCA calculator* hereafter), no feedback is established, i.e. the results of the LCA do not influence the simulation models upstream of the LCA model. In type (iii) couplings, the results of the LCA are fed back to the simulation models (or *simulators*) upstream and can influence their results in a new simulation step. The simulators upstream of the LCA calculator can be different. For instance, they can be an Agent-Based Model (ABM) [5], a process-based simulator [6], an economic equilibrium model [7], etc. In Marvuglia et al. [5] and Davis et al. [8], every run of the ABM generates an instantiation of the LCI (acting on the foreground system in the case of [5] and on the background system in the case of [8]) that can be used by the LCA calculator to obtain the corresponding environmental impacts. If a feedback loop is activated between the LCA calculator and the simulator (in this case, the ABM simulator), the results of the LCA can be used as a new starting condition for the ABM, which will consequently adapt and produce new results (i.e. a new LCI) on its second run. This process can be repeated until a specific predefined convergence condition is met.

Since simulators typically need to be run via several iteration steps, the hard coupling between the simulator and the LCA calculator is significant, because, at each iteration, the information needs to flow automatically between the two. This last type of coupling is the most difficult to accomplish, and it is not easy to find examples of fully-fledged GIS-LCA hard coupling in the literature. This is because it requires advanced informatics skills and a deep mastery of the GIS tools. Some specific LCA calculators, like Brightway2 and OpenLCA, already contain built-in modules to allow the seamless processing of GIS data to produce regionalised inventories, and therefore they perfectly lend themselves to achieving a hard GIS-LCA coupling.

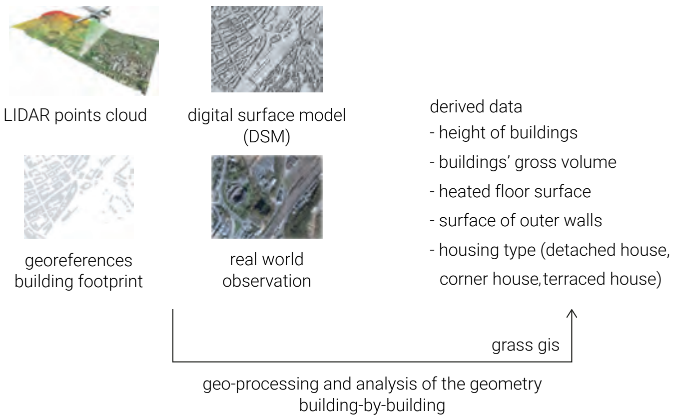

Figure 10

Urban spatial data processing and derivation of additional relevant information about buildings. GRASS GIS is used to process thematic layers in order to derive additional spatial data

Figure 11

Schematic representation of the data processing flow in DAEDALUS. The different calculation modules interact with the building stock database to fetch and record information

However, it is challenging to identify studies in the scientific literature where this hard coupling has actually been implemented and sufficiently well documented. Even in the most advanced studies where GIS-based information was processed in the context of LCA [4], [9], the authors generally do not clearly specify whether the coupling was done in an automatic fashion or in a semi-automatic one (i.e. the user needs to manually export the outputs from the GIS and import them into the LCA calculator, and vice versa). In other words, it is not possible to unequivocally classify them as examples of soft coupling or hard coupling. It is instead more common to find studies in which GIS-based information is processed with a dedicated software tool, such as ArcGIS [10] or GRASS GIS [11] before a soft coupling is realized with the LCA software used. An example of well documented hard coupling between a process-based simulation tool and an LCA calculator is given in Igos et al. [6]. However, this study does not involve the use of GIS-based data.

AN EXAMPLE OF GIS AND LCA COUPLING

An example of GIS-LCA coupling was developed in the framework of the DAEDALUS project ('Developing An integrated gEospatial approach for DynAmic Life cycle assessment of housing stock retrofit at the Urban Scale' - Grant agreements AFR-7579115) supported by the National Research Fund, Luxembourg (FNR). In DAEDALUS, spatial data coming from different sources were processed using the GRASS GIS software in order to derive additional spatial information at the city level to obtain more precise LCIs for the city of Esch–sur-Alzette, in Luxembourg, as depicted in Figure 10.

The obtained data (stored in a PostGIS database), as well as the data on building components and heating systems obtained from different sources (stored in a PostgreSQL database), were then used by the LCA calculator to perform an LCA of different refurbishment scenarios at the scale of the entire city [11], [12]. In the framework of DAEDALUS, the coupling was still of the soft type, and the information flow between the GIS and LCA parts of the model was still semi-automatic. The results of the LCA module (in this case CO_2 savings potential after building refurbishment) were then visualised on a web-based interface. The entire process is schematically described in Figure 11.

This section introduced the challenges and benefits of coupling GIS and LCA very briefly and summarised the data collection and data processing phases performed in the framework of the DAEDALUS project. The integration and processing of spatial information in the LCA are beneficial in every phase of an LCA study, especially in sectors such as agriculture, transport, building and construction, and electricity production and distribution. In the goal and scope definition phase, GIS can be used to define the boundaries of the study according to the quality of the available data and the relevance of specific impact categories compared to others, depending on the process studied.

In the LCI phase, it can help to localise the sources of the emissions and characterise them, e.g. defining the type of soils, land use, crops, etc. in agricultural studies, or locating the main transportation axes in an LCA of mobility. In the impact assessment phase, GIS can be used to determine the level of water stress as a function of the properties of the local watershed, for instance. Finally, in the results interpretation phase, GIS can assist in the creation of maps of potential CO_2 savings in specific scenarios evaluated, as shown, for example, in Figure 11. However, despite the importance and usefulness of integrating the representation and processing of spatial information in LCA, a complete coupling of GIS and LCA is still missing in most of the current LCA studies due to the informatics skills and time investment required.

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PARAMETRIC LCA IN EARLY DESIGN STAGES

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Initial design phases have the highest influence on the environmental impacts of a building throughout its lifetime. Currently, the environmental performance of buildings is rarely optimised holistically based on Life Cycle Assessment (LCA). Missing information and the complexity of the method are two main reasons amongst others. Therefore, simplified approaches are needed, especially in the early design phases, to provide assumptions for missing data. The results of applying the parametric LCA approach using a plug-in for SketchUp called CAALA to a real case study are discussed.

ARCHITECTS' INFLUENCE ON THE ENVIRONMENTAL IMPACT

The construction sector has a very high impact on the environment and is responsible for one-third of global greenhouse gas emissions [1]. Architects can, from the design phase, broadly define the environmental impact that a building will cause throughout its lifetime. Due to the implementation of energy efficiency regulations in European countries in recent years, the operational impact of new buildings has been dramatically reduced, which has resulted in a greater focus on the impact of embodied carbon. In new, energy efficient residential buildings, the embodied carbon makes up about half of the total greenhouse gases emitted in a lifetime of 50 years [2]. This clearly shows the need for a holistic assessment of the whole life cycle. Life Cycle Assessment (LCA) is increasingly applied to assess the environmental performance of buildings for certification purposes, e.g. DGNB [3].

However, this post-design evaluation through LCA is not sufficient on its own as it does not improve the environmental performance of the design [4]. To minimise environmental impacts, an integration of LCA into the architectural design process is needed, especially in the early design phases, as these have the highest influence on them [5].

PARAMETRIC LIFE CYCLE ASSESSMENT

The basic concept of the parametric LCA (PLCA) approach is combining the principles of parametric design with a simplified LCA method. [6]. The method follows the framework of EN 15978. The operational impact from the use phase of the building (life cycle module B6) is based on a quasi-steady-state energy demand calculation using monthly energy balancing [7]. The embodied impact includes material production, replacements and the end-of-life and the recycling potential (life cycle modules A1-A3, B4, C3, C4, and D). The correct calculation of the PLCA model was verified by comparing the results of a real building to the results of a published LCA study [8].

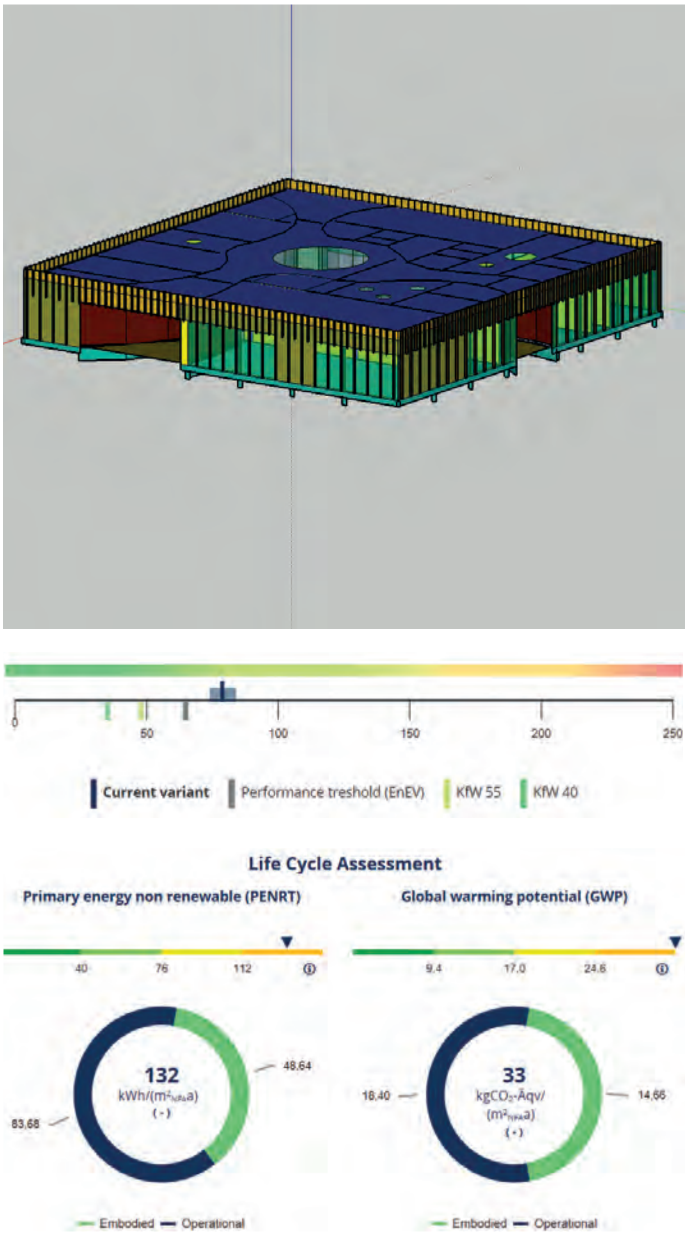


Figure 12

The graphical user interface of CAALA showing the input of geometry in SketchUp and the input in the browser window. The browser viewport is divided into the input of boundary conditions, building materials and HVAC systems on the left and the output of results on the right

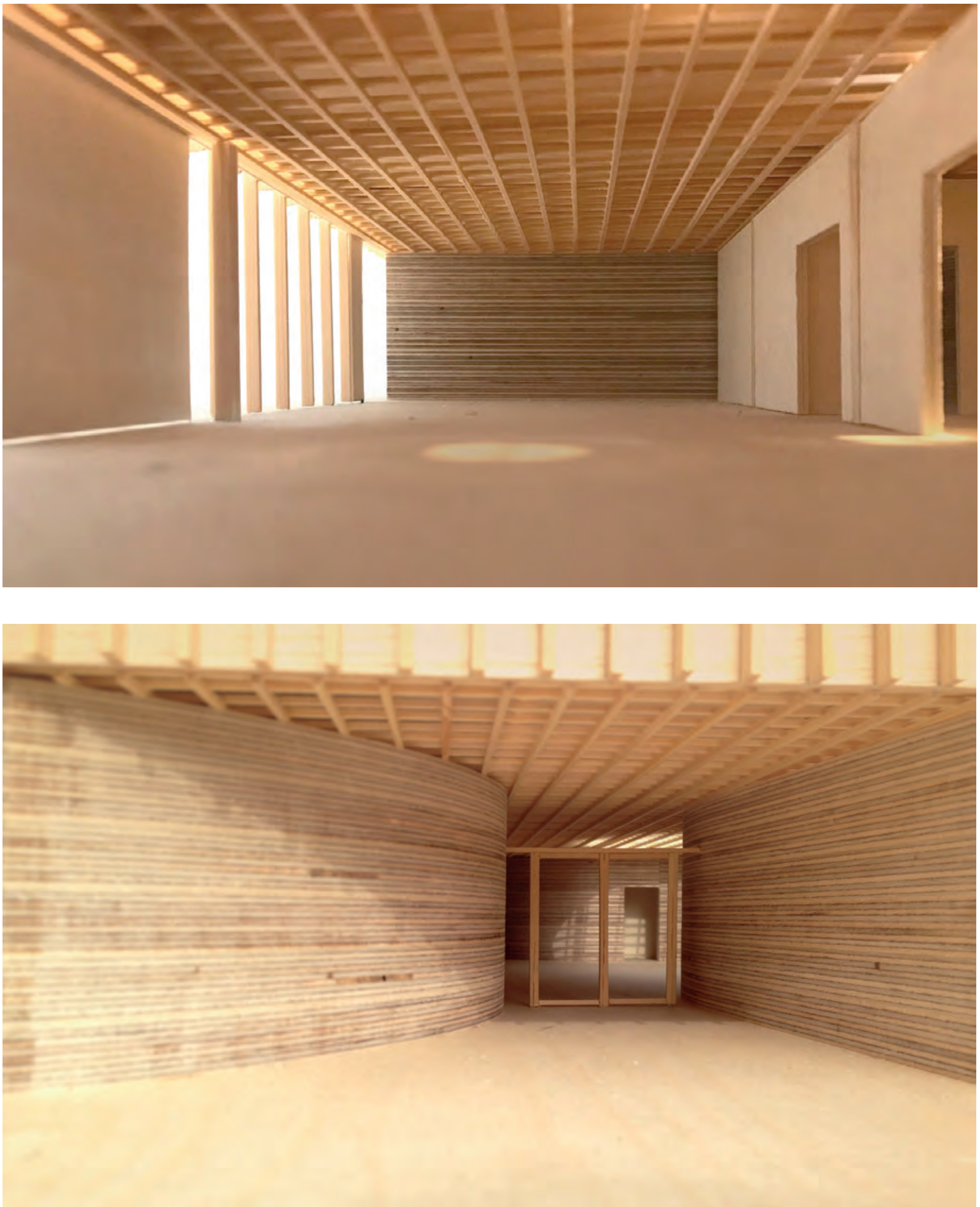


Figure 13

Photographs of a scale-model of the design (Courtesy © HESS / TALHOF / KUSMIERZ Architekten und Stadtplaner / BDA)

Figure 14

Photograph of a scale model of the design (Courtesy © HESS / TALHOF / KUSMIERZ Architekten und Stadtplaner / BDA)

Figure 15

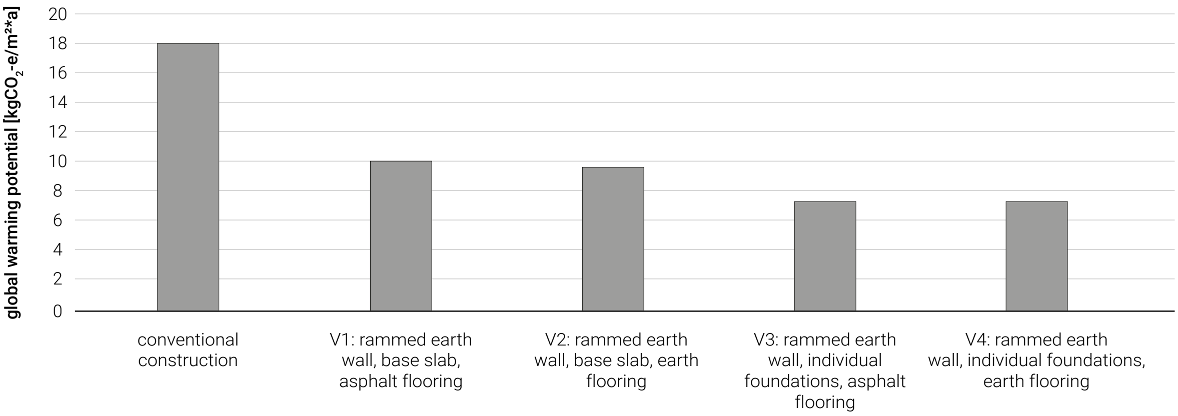
Visualisation of the case study building 'Centre for environmental education' in Augsburg, Germany (Courtesy © HESS / TALHOF / KUSMIERZ Architekten und Stadtplaner / BDA)

To make the PLCA method available for a wider public, cloud-based software called CAALA [9] has been developed. Currently, the tool works as a plug-in for SketchUp and Rhinoceros. In both cases, the basis is a simple 3D model similar to a thermal model for energy simulation. CAALA automatically retrieves the surface areas and transfers them to the calculation engine on a server. Boundary conditions, materials and Heating, Ventilation, and Air-Conditioning (HVAC) systems are defined in a browser window. The tool uses a material library in the backend. The physical properties are based on DIN 4108-4 [10]. The environmental data of the German national database ökobau.dat [11] is used. Specific Environmental Product Declarations (EPDs) from manufactures can also be manually added to the tool's internal database. All input parameters are pre-defined with default assumptions and can be refined by the users. In this way, it is assured that the calculation can always be carried out. The results for the whole life cycle are visualised in a browser window (Figure 12). The calculation is real-time [12].

CASE STUDY

HOT Architects from Munich applied CAALA for the design of a new centre for environmental education in Augsburg, Germany (see Figure 13-15 for illustrations of the final design). The goal was to obtain quantitative results on the embodied environmental impact (Global Warming Potential) of different materials. In the first step, the curved, load-bearing interior wall was modelled in two variants: a rammed earth wall and a conventional concrete wall. Therefore, a simple conceptual 3D model was defined in SketchUp for CAALA.

Figure 16
Results of different variants regarding the materials for the load-bearing interior walls, the foundations and the floor covering compared to a conventional type of construction



The results showed that the rammed earth wall could save a significant amount of embodied global warming potential (GWP). In a second, more detailed step, the building was modelled, including shading elements, columns, and foundations (see Figure 12). Four different variants all consisting of a rammed earth wall but varying the type of foundation (single foundation vs base slab) and the floor covering (earth vs asphalt) were modelled. The results in Figure 16 show that Variant 1 can save about 45% of embodied GWP compared to conventional construction. The use of individual foundations can save about another 10%, while the change of the floor covering has very little influence. Finally, the architects used the results to convince the client to invest in a rammed earth wall with individual foundations, although the investment costs were higher than the conventional construction. They did not choose the earth floor because the costs were higher and the savings in GWP small. The application to a case study demonstrated the benefits of using LCA in the design phase to allow for decision-making based on quantitative results. It can be concluded that through tools, it is now feasible to integrate LCA into the design process. Finally, to overcome the current misconception that environmentally friendly solutions are too expensive, tools should include and couple LCA to Life Cycle Costing (LCC) in the future.

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PARAMETRIC LCA ADOPTION IN PRACTICE

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In the period from 2015 to 2018, five architectural design studios in Scandinavia, led by the Technical University of Denmark, used life cycle assessment (LCA) as an active design driver in their work [1]. Nearly all of the examined projects began with or ended in analyses that are different from what it is expected as being a common use of LCA. The realisation was that LCA's were not the target itself for most projects, and when they were, the LCA drove the project into other areas of analysis far beyond the narrow scope of LCA. Typically, LCA involves an accounting of the quantity and type of materials that will be used in the building to understand and predict the embodied and operational impact of the building from the early design stage. The lesson learned from these projects was that the actual prediction of material impacts was given little value without the understanding of the current target and its consequences on the critical design parameters.

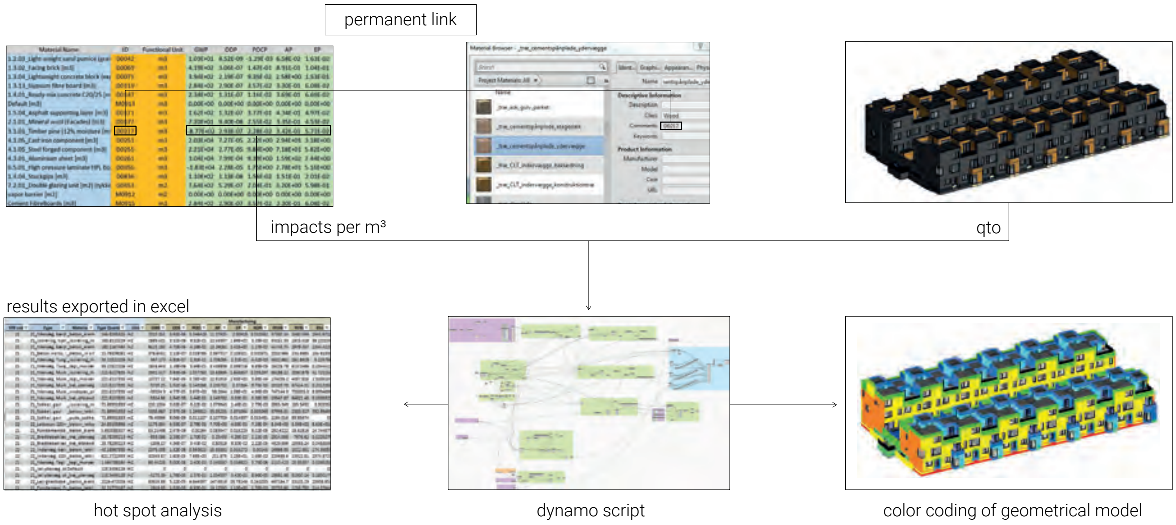
REGENERATIVE DESIGN AND LCA

Although LCA methodologies are increasingly being standardized using regulations, there is currently no performance target to be met, as is commonly seen in other areas such as maximum building energy demands defined in national and European codes. Targets may be defined by following assessment protocols such as those delivered by the German Sustainable Building Council (DGNB) and many other currently ongoing projects. Pinpointing the target is problematized as no standardised reference study period (RSP) is defined [2]. It matters if the building is evaluated to last 50 or 100 years [3] (e.g. a 100-year period will increase the dominance of the operational phase). For regenerative design, which aims for buildings that have a positive impact on the environment, the RSP may even prove to have greater importance than ever. It is clear that in the near future, buildings will need to be at least carbon neutral during their life cycle. However, one question remains open; *how long does it take to reach the carbon break-even point for new buildings?*

The first recommendation for LCA in early design stages is as simple as: '*define the target lower than the LCA of the current design proposal*'. This simple process will help considerably more than any discussion on which components should be included and what RSP is more reasonable. In this sense, LCA is not necessarily about predicting the future in great detail. It is simply impossible to *know* if a building will last for 50 or 100 years, or even longer: some of the concrete tower blocks built in the 1970s and 1980s were demolished only a few decades after being built, while others are now seen as heritage and as such are protected from demolition. LCA should be used to compare building designs, and not to pretend to pinpoint the exact emissions and lifetime of a building. LCA can be used to provide insight into the comparative environmental impact of design alternatives in both a 50-year and 100-year timeframe.

ANALYSING THE 'CONSEQUENCES OF LCA'

Many papers that focus on LCA (parametric or not) have yet to include the most important factors of real practice; *LCA should be used to inform and then change design rather than to assess the final solution of design.* As LCA is seen as a design driver, it is process-driven and not useful as an absolute predictor. As it does need to inform change, the consequence of change has to be understood as well. If not properly understood, LCA will remain in the realm of hypothetical and ideal solutions to problems and will therefore not address the (holistic) design needs of architecture and engineering. Based on the integration of LCA, low environmental impacts are prioritised over other aspects. However, as a consequence of prioritising low environmental impact alternatives, other aspects of a design will change, such as form, aesthetics and functional program. In our experience, during many projects, this also effected changes in the static structure, changes to indoor and outdoor comfort, changes in acoustic performance, changes in risk of mould growth and many more changes. The reasoning of choosing one set of materials over another is not only about the environmental impacts in CO_2-equivalents, but also about the quality of the building and multiple other aspects where LCA does not provide answers. However, as White puts it: *'To compare different structural alternatives in very early stages is essential to project climate impact (of LCA).' – White Arkitekter* [1].



Caring about the consequence of the LCA choices is equivalent to caring about both the beneficial and adverse impacts on design. The way the five studios sought to address the analysis of both LCA and the consequence of choosing low impact alternatives was by formalising analyses as the product of an integrated dynamic model [4]. This is a combined (parametric) model composed of a geometric model controlled in a design tool dynamically coupled to a visual programming language (VPL), which is in turn dynamically coupled to a building performance simulation (BPS) environment.

Figure 17
An integrated dynamic model with a focus on LCA in Revit, which later became the LCA plugin for Dynamo 'Aeforos' (Source: [6])

The design tool is defined as the designer's preferred CAD/BIM tool (for an example of such a model, see Figure 17) to minimise the change of the design process and need for remodelling. Any programming language can substitute the VPL, but keeping the visual/scripting element helps to prototype and allows more flexible use of the BPS. The choice of BPS is defined by the need for the specific analysis, whether dealing with structural analysis, dynamic thermal comfort analysis or any other type of analysis

It is possible to construct generic models that behave as tools that can foretell thousands of parameter variations of the design. This can be done because of the modularity and plugin-structure of the VPLs, such as Grasshopper and Dynamo, which provide numerous pathways to some of the validated Open Source BPS tools (e.g. OpenStudio, Daysim, Radiance via Honeybee and Ladybug [5]) and several in-house developments. Plugging into this platform makes the aggregation of areas and impact metrics simpler and much faster than any traditional manual approach.

As an example, the architectural studio White Arkitekter used such a platform to design a canopy between existing buildings that reaches break-even for climate impact for conventional renovation [1].

Another example is ‘Aeforos’ [7]; a dedicated Dynamo-plugin for LCA based on Ökobau data structured neatly in a way that the architectural studio of Vandkunsten could directly apply in their day-to-day work. This meant that many of the worries about quality assurance and modelling precision were taken out of the equation. As Vandkunsten put it, *‘Perhaps the biggest issue with developing a tool like Aeforos is the task of keeping the software and databases updated’* [1].

Out of this experience, a recommendation that can be given for LCA in early design is that when handling large amounts of data and variations of design parameters, utilizing VPLs and the optional connectivity to other dedicated integrated dynamic models (such as calculating energy consumption in the use phase) as a test-bed for analysing life cycle impacts is both flexible and faster than using standalone tools. The challenge for the users is to understand and be comfortable in using scripting languages to perform an LCA.

Applying LCA to the design process in practice is a demanding task for many studios and designers. Adopting parametric LCA is even more demanding as it requires knowledge beyond the domain of LCA. In this article, two of the challenges practitioners face are discussed based on the experiences of working with five architectural firms. A) how to handle the targets and reference study periods: LCA should be seen as a tool to compare design alternatives, not as an exact predictor of impacts, and B) how to model and handle geometry and database values effectively by means of experimenting with an integrated dynamic model, dynamically coupling a geometric model (in BIM/CAD) to a visual programming language (VPL), which is in turn dynamically coupled to a building performance simulation (BPS) environment.

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PARAMETRIC OPTIMISATION OF CARBON FOOTPRINTS

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The built environment is responsible for 40% of energy consumption and 40% of CO_2 emissions in the European Union [1]. With the rising carbon dioxide emissions linked to human activities and the high share of them linked to the building sector, strategies and design approaches that minimise the environmental impact of buildings are needed. With the goal in mind to reach the net zero carbon goal by 2050, it can be said that solutions should be not only 'sustainable', but they should be 'regenerative'. Architectural design could and should lead to not only lowered environmental impact of buildings but also be an element of positive change. The study analysed here uses a parametric model to investigate the possibility to influence a building's Total Carbon Footprint in the early stages of design development. The optimisation process was assisted with an evolutionary algorithm, which helped to generate and select the lowest Total Carbon Footprint version of the design.

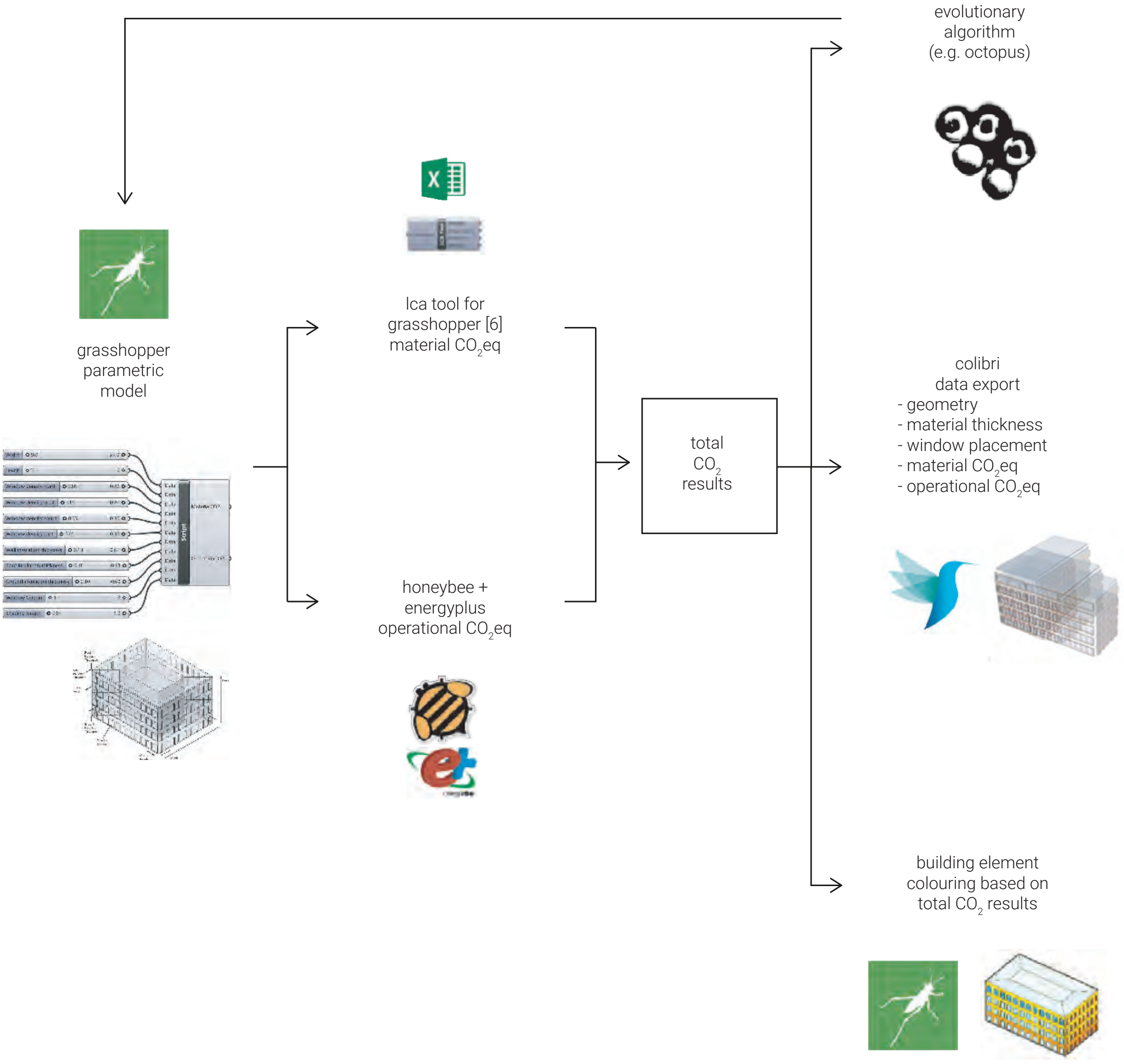
The architectural design process typically follows similar stages: early sketching, concept development, building drawings and execution drawings [2]. The ability to change the design is usually much higher in the early phases, and the possibility diminishes as the project progresses [3]. One of the standard evaluation tools used to analyse a building's environmental impact is Life Cycle Assessment (LCA) [4]. This method, which is usually applied at the end of the design process, demands very detailed knowledge of the object. This means that it cannot be used as a design tool, but typically only as an evaluation tool. Consequently, the possible advantages that would derive from early design decisions leading to the reduction of environmental impacts are lost.

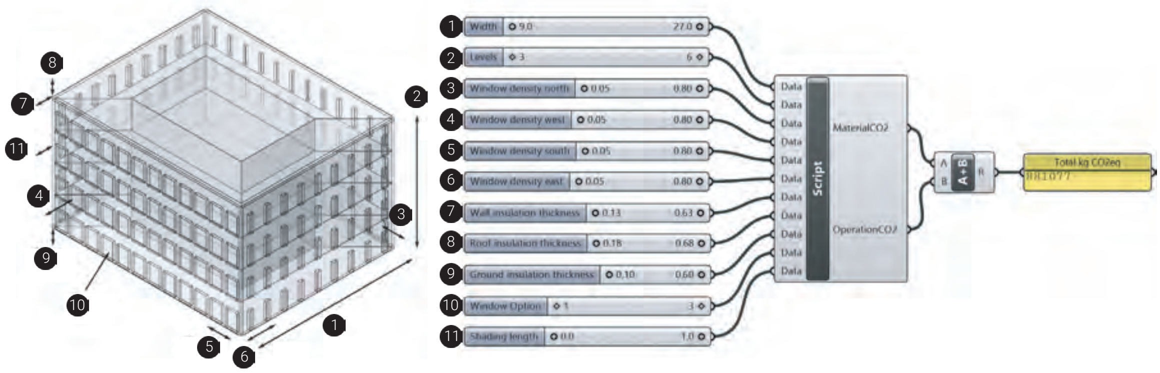
Figure 18

The image shows the optimisation process that was used in the study. Different programs and plugins were used, but the Grasshopper environment was the basis. After clicking start on the Octopus Evolutionary Algorithm plugin, the only thing was to wait for the results – the generation and simulation of 400 different building models took around 40 hours on a standard PC

Figure 19

The model represents a simple multifamily housing complex. All dimensions of the elements are defined by parameters, which gives an easy option to test various versions. The right side of the image shows the sliders inside the Grasshopper interface. Each slider represents one parameter that can be easily changed between the defined minimum and maximum values


evolutionary
algorithm
(e.g. octopus)
grasshopper
parametric
model
lca tool for
grasshopper [6]
material CO_2eq
honeybee +
energyplus
operational CO_2eq
total
CO_2
results
colibri
data export
- geometry
- material thickness
- window placement
- material CO_2eq
- operational CO_2eq
building element
colouring based on
total CO_2 results


1
2
3
4
5
6
7
8
9
10
11
Width 9.0 27.0
Levels 3 6
Window density north 0.05 0.80
Window density west 0.05 0.80
Window density south 0.05 0.80
Window density east 0.05 0.80
Wall insulation thickness 0.13 0.63
Roof insulation thickness 0.18 0.68
Ground insulation thickness 0.10 0.60
Window Option 1 3
Shading length 0.0 1.0
Data
Script
MaterialCO2
OperationCO2
A
B
A+B
R
Total kg CO2eq
881077

LCA PARAMETRIC MODELLING

In recent years, the growing popularity of parametric design tools can be observed. One of the reasons for this growth is that they can generate, analyse and compare several design solutions and allow for the selection of the most efficient parameter configurations to optimise towards a given objective, for example, the minimisation of life cycle impacts. A Parametric LCA method has been proposed by A. Hollberg [5]. The method calculates both the embodied and operational impacts using a script created in Grasshopper. The script was designed to lower the time required to perform LCA in the early design phases, allowing easy implementation of the carbon footprint assessment in architectural practice [5]. A similar approach to the parametric calculation of LCA has been proposed by Negendahl, Otovic and Jensen [6] using an LCA Tool for Grasshopper to calculate the embodied carbon, and Ladybug and Honeybee to calculate the operational energy. Parametric modelling allows analysing many different options, but this also increases the time needed to run the analyses. There is a need for algorithms that improve the time efficiency of the process. Naboni et al. [7] investigated the impact of building shape, façade design and material selection on operational energy consumption. More than ten different building features were declared as variables. A genetic algorithm was used to improve the time efficiency of the method [7]. An overview of the different tools that were combined in this optimisation process is presented in Figure 18.

A CASE STUDY OF BUILDING OPTIMISATION

The objective of this study is the optimal form in terms of minimal lifecycle environmental impacts of a multifamily building located in Warsaw [8]. For this study, a parametric model of a building was created. Eleven different parameters that describe the model were defined – as presented in Figure 19. The study focused on the features that change the architectural design of the building. The material choice was fixed, but the insulation thicknesses were one of the parameters. The energy model was modelled in Grasshopper according to the instructions from ASHRAE Standard 90.1 – with 4.6m thermal zones for each side of the building and a common core, with separate zones for each level [10].

GENETIC EVOLUTIONARY ALGORITHM

A genetic algorithm, which is a type of evolutionary algorithm, is an efficient approach to solving optimisation problems. In this case study the task was to minimize (optimise) the carbon footprint of the building, which was considered to be a sum of Embodied Carbon (A1-A3 LCA phases) calculated by the 'LCA Tool' [6], and

Operational Carbon (B6 LCA phase), calculated with Ladybug Tools with EnergyPlus[9]. The optimisation process was carried out by using a specific genetic algorithm plugin for Grasshopper – Octopus [2].

The way the genetic algorithm works can be described in steps: 1) Generate random starting population – in this step, the algorithm created a set of 20 different building versions using the 11 predefined sliders. 2) Evaluate fitness of the generated building models – in this step each of the building models was evaluated according to the Embodied and Operational Carbon to calculate the Total Carbon Footprint 3) Select the building models with lowest Total Carbon Footprint, perform genetic operations and generate a new set of 20 buildings. Steps 1) and 2) were repeated to generate 20 sets of 20 building models, resulting in 400 design solutions.

Figure 20 and Figure 21 present the geometry and building features of the final optimised models. By comparing the initial random population of the first generation (20 models) with the final generation (20 models), we can see if the algorithm helped to optimise the building's Carbon Footprint. The optimisation process resulted in lowering the total carbon footprint of the building by around 32%. In the study, it can be observed that the Operational Carbon was a more important factor in the selection of the optimal solution.

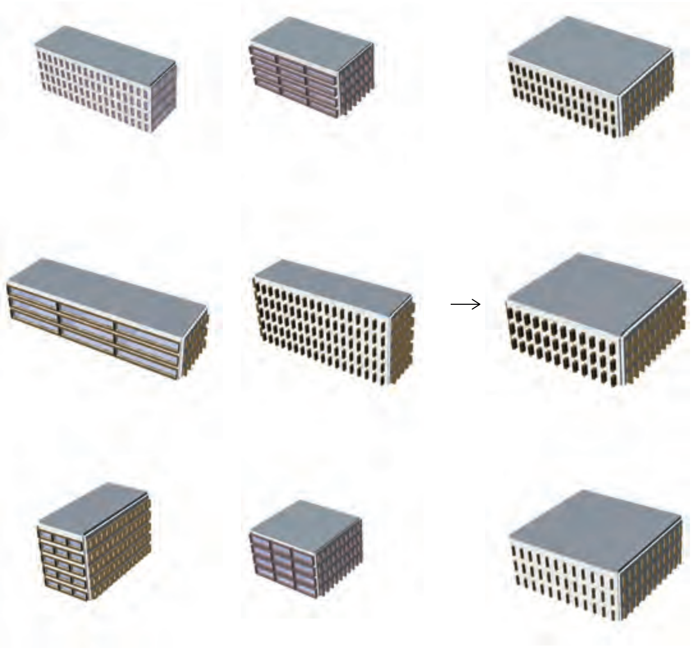


Figure 20

The evolutionary algorithm at first generated varied solutions with different heights, widths and window distributions (randomly selected cases). The selected best cases, however, look very similar to each other (here 3 out of 20 best cases are presented)

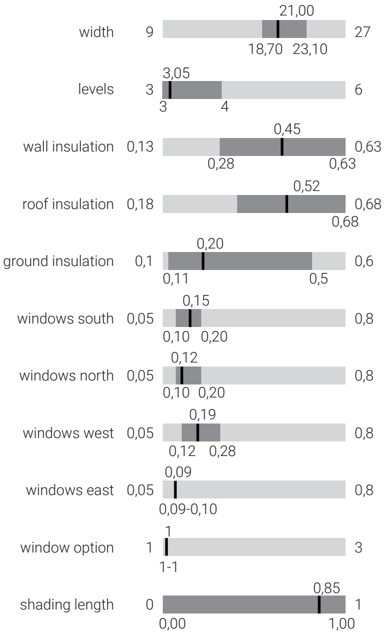
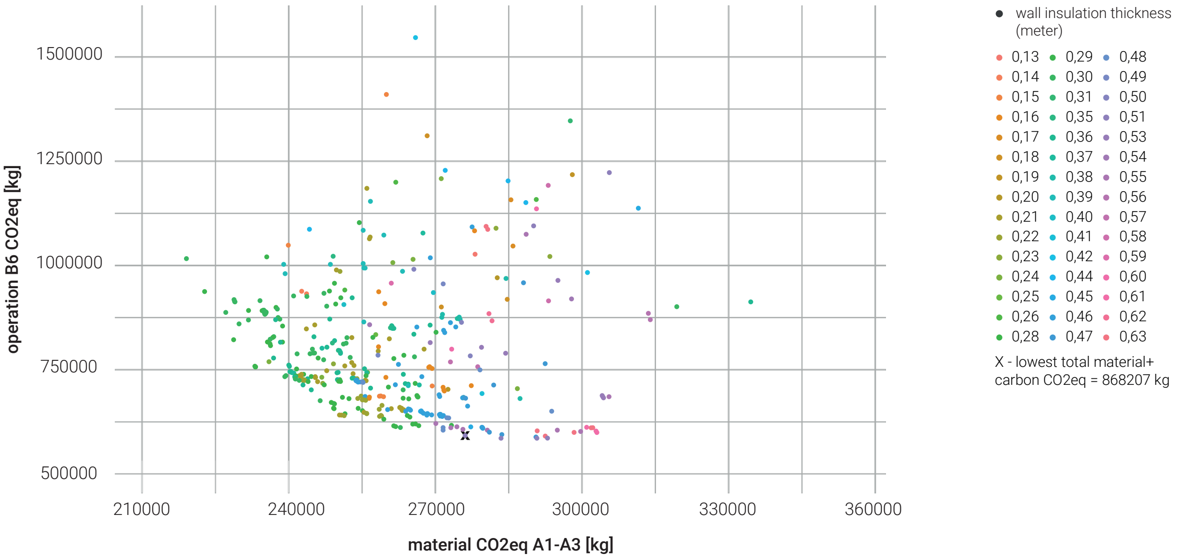
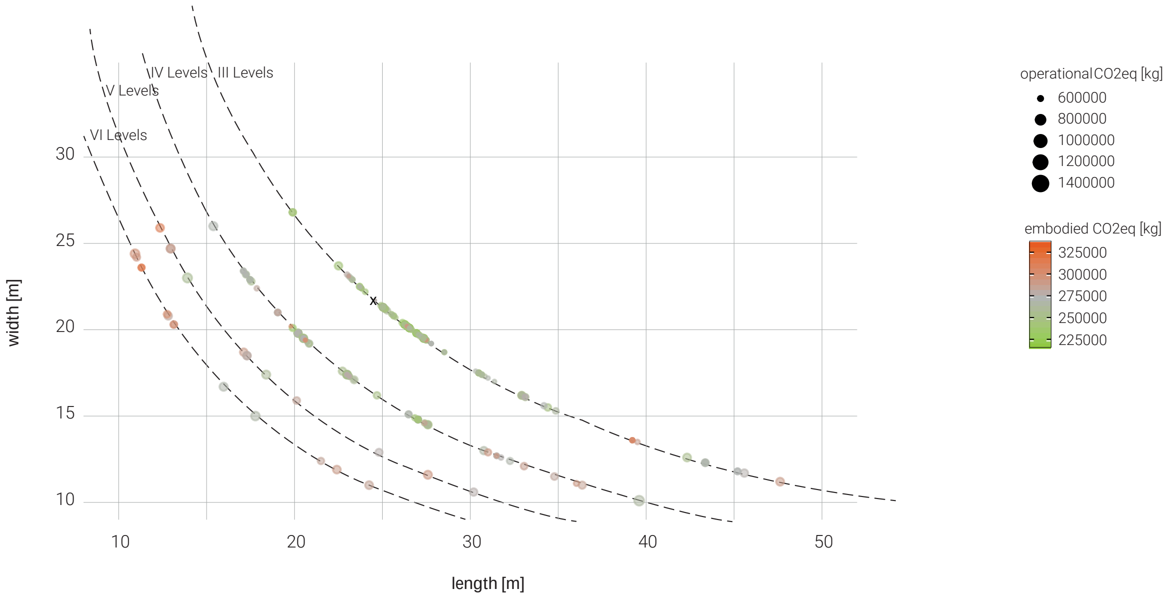


Figure 21

The results of the optimisation process: the optimal building features for the lowest Carbon Footprint. Light grey shows possible parameter values. Dark grey shows the range of the parameters in the best 20 cases. The black tick represents the average value of each parameter in the 20 best cases


1500000
1250000
1000000
750000
500000
operation B6 CO2eq [kg]
210000
240000
270000
300000
330000
360000
material CO2eq A1-A3 [kg]
X
● wall insulation thickness (meter)
0,13 0,14 0,15 0,16 0,17 0,18 0,19 0,20 0,21 0,22 0,23 0,24 0,25 0,26 0,28
0,29 0,30 0,31 0,35 0,36 0,37 0,38 0,39 0,40 0,41 0,42 0,44 0,45 0,46 0,47
0,48 0,49 0,50 0,51 0,53 0,54 0,55 0,56 0,57 0,58 0,59 0,60 0,61 0,62 0,63
X - lowest total material+ carbon CO2eq = 868207 kg


IV Levels
III Levels
V Levels
VI Levels
30
25
20
15
10
width [m]
10
20
30
40
50
length [m]
x
operational CO2eq [kg]
600000
800000
1000000
1200000
1400000
embodied CO2eq [kg]
325000
300000
275000
250000
225000

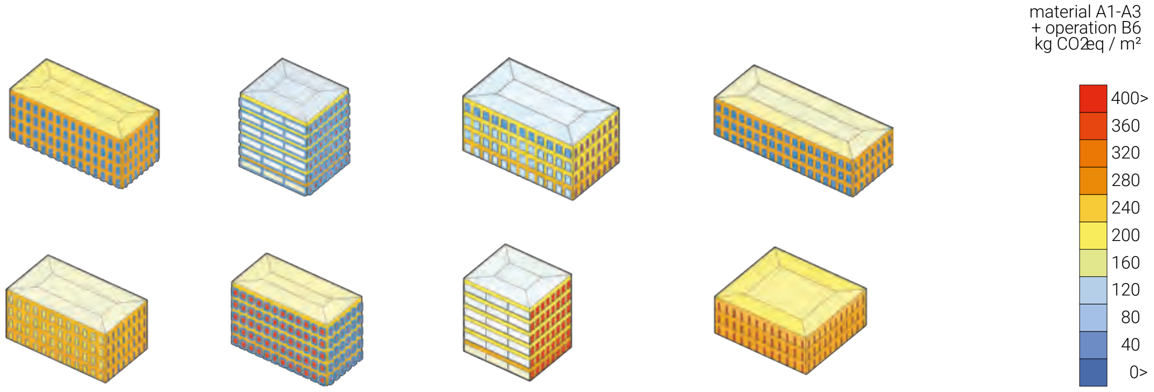

material A1-A3
+ operation B6
kg CO2eq / m²
400>
360
320
280
240
200
160
120
80
40
0>

Figure 22

Scatterplot of all the simulations. Operational Carbon vs Embodied Carbon. The optimal solution has been marked with an 'x' symbol. The colours represent the insulation thicknesses selected in specific cases. It can be observed that the optimal insulation thickness is not the maximum value possible, but it is rather a trade-off between Operational and Embodied Carbon

Figure 23

The effect of varying building dimensions on the Building Operational and Material Carbon related CO_2 emissions. The total area of the building was kept constant at 1600 m2, but the parameters allowed to change the width and number of levels, which also influenced the building length. It can be seen that the optimal solution lies on the III levels line (marked with an 'x' symbol)

Figure 24

Colour-coding the environmental impact helps the designer to identify the areas that require attention. In this example, the results from the LCA Tool and Honeybee + Energy Plus Simulation are calculated together to get a rough overview of Life Cycle Carbon Emissions of building elements (for the Operational carbon, the data from Energy Surface Flow is used to estimate Heating/Cooling load share of each element). Visualisation is done in Grasshopper

The scatterplot shows that the optimal solution is not the one with the lowest Embodied Carbon, but at the same time, it is very close to the lowest Operational Carbon solutions (Figure 22). It can be seen that building models with a plan closer to a square shape resulted in lower Total Carbon Footprint, but the study shows that the algorithm still preferred a more extended southern/northern than western/eastern façade (Figure 23). The script almost exclusively selected options with three-level high buildings, while there was the possibility to generate a building between three and six stories. This choice could be motivated by the fact that higher buildings need higher staircases and the staircases are made mostly out of material (concrete) with an elevated embedded CO_2. Colour-coding the environmental impact helps the designer to identify the areas that require attention. Figure 24 presents the colour-coded outcomes for individual building components, including both operational and embodied impacts.

The study tested a parametric approach to the optimisation of an architectural design. It showed that using an algorithm can help to decide which design options are better for a specific case. Using this method can help architects understand how different building features influence the Total Carbon Footprint. The results confirm that early design decisions have a high impact on the final carbon footprint. This means that architects should try to include considerations about Total Carbon Footprint early in the design process, as at this moment making changes to the design is still easy, and they can lead to significant Carbon Footprint savings.

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INTEGRATIVE LCA-BASED DESIGN WITH BIM

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Integrative Process Design offers the opportunity to foster a cross-disciplinary design method to achieve more sustainable building design. Conventional design and construction processes involve a series of handovers of documentation and drawings between professionals and with clients. The Integrative Process (IP) seeks to design and construct projects focused on sustainability by engaging all project team members in an intentional process of discovering beneficial interrelationships and synergies between disciplines [3]. Collecting and managing data across different disciplines and consultants along the project lifecycle could be enhanced by a collaborative data environment. Often, this integration is not easily achieved due to time constraints and the complex interaction of different disciplines. Where traditional computer-aided-design fails to manage the growing complexity of data needed, Building Information Modelling (BIM) has become an efficient method to collect and evaluate project information from different disciplines. BIM could become the repository of data from various disciplines in an integrated process.

MANAGING DATA ACROSS DIFFERENT DISCIPLINES AND CONSULTANTS ALONG THE PROJECT LIFE-CYCLE

At its core, BIM is a process for creating and managing information on a construction project across a project's lifecycle. It is aimed at being used across different actors of the construction sector in a collaborative cross-disciplinary virtual environment. One of the outputs is the digital description of the aspect of the built asset [4], which can include the data needed to perform a Life Cycle Assessment (LCA).

LCA is a method to assess environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. Integration of the building dataset managed with BIM (including material quantities for example) and other datasets is needed to accurately perform an LCA (such as *embodied carbon coefficients* (ECCs) and *Environmental Product Declarations* (EPDs)).

Two workflows are currently used. One is to extract the material quantities from the BIM model and import them into a custom-made spreadsheet. Subsequently, environmental impact information for each material is inserted based on external databases of ECCs or EPDs. This method can take advantage of data management using visual programming tools to extract and organise available information in the models efficiently. The second is to take advantage of BIM's interoperability: certain LCA software tools allow for importing (or even being coupled to) a BIM model in the form of open format (for example IFC) and subsequently provide access to material databases to conduct the LCA.

In Computer Assisted Design (CAD), project information and specifications are spread across various drawings, reports and documentation. This means that useful data could be lost or interpreted differently by different team members. Conversely, BIM represents the digital description of every aspect of the built asset. Besides drawing and documentation, BIM models are the repository of project information for a shared design process between the project team, sustainability consultants, contractors and facility managers [5]. BIM allows moving from a linear project approach, where information is fragmented across teams, to a more integrative and collaborative workflow, where the models become the repository of project information and are available to different stakeholders (see Figure 25).

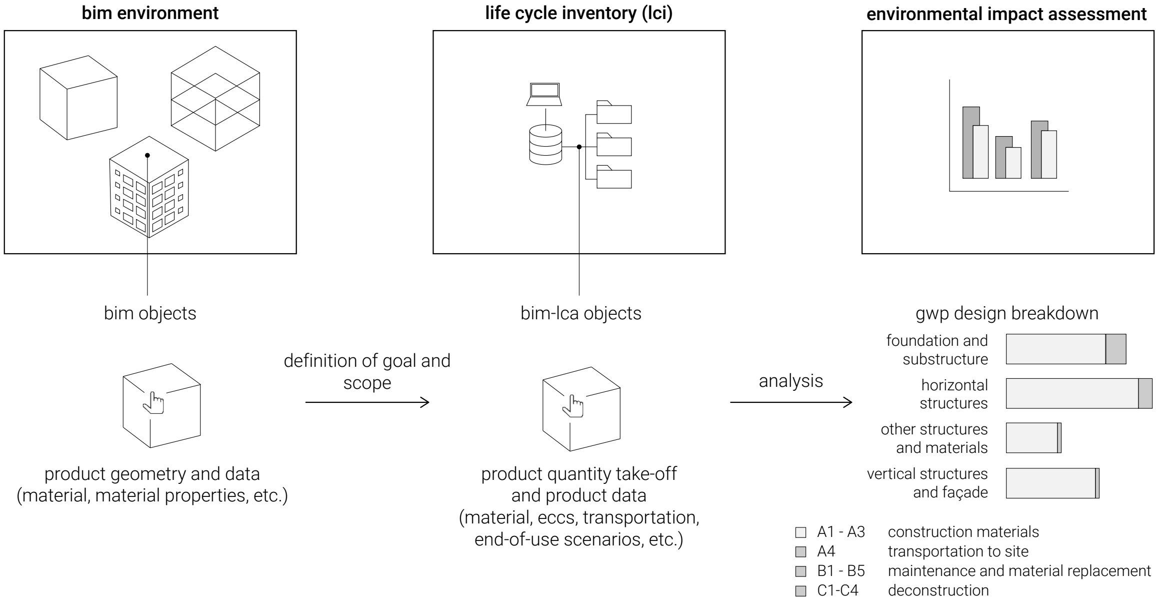


Figure 25

Example of Integrated workflow between BIM and LCA. Parameters of the BIM model are integrated with Life Cycle Inventory data to enable environmental assessment of the project

Figure 26

Chicago Public Library (Courtesy SOM, © Jon Miller for Hedrich Blessing)

Figure 27

Chicago Public Library (Courtesy SOM, © Jon Miller for Hedrich Blessing)

A CASE STUDY OF BIM-BASED DECISION-MAKING

The construction sector consumes a significant proportion of the world's resources, mostly in the form of material usage and energy resources required for raw material extraction, transportation and manufacturing [1]. Embodied carbon represents one of the many factors impacting the life cycle global warming potential (GWP) related to the production of the construction materials, the building's construction, material replacement and end-of-life treatment. The lack of a standardised approach for the computation of embodied carbon, along with a lack of reliable emission factor data for building materials and processes, causes many variations in the results of carbon assessments.

A LEEDv3 certified building in the USA (see Figure 26-28 for visualisation and photographs of the building) was studied to evaluate the embodied carbon sensitivity to different assumptions using project-specific data [2]. The research reveals which lifecycle stages and building components are more sensitive to the tested variations for a low-rise steel-framed building (see Figure 29 for life cycle stages).

The sensitivity analyses focus on four of the most important factors typically used to perform a whole life building analysis: ECCs based on recycled content of metal materials, wastage during construction, transportation distance from manufacture to site, and embodied carbon coefficient for freight transportation. The sensitivity analysis demonstrates which assumptions are most relevant to the carbon footprint and reveals that steel-framed buildings with extensive aluminium curtain walls display large variability in the calculated embodied carbon depending on the assumptions used (i.e. regarding regional variabilities of the recycled content of steel and aluminium, product wastage, transportation of material to the site, and expected repair and replacement).

Figure 28
Chicago Public Library (Courtesy © SOM)

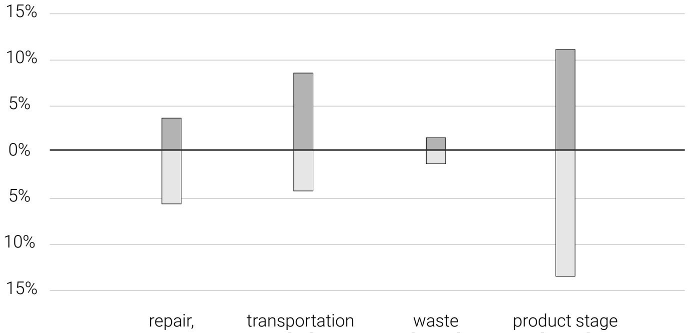
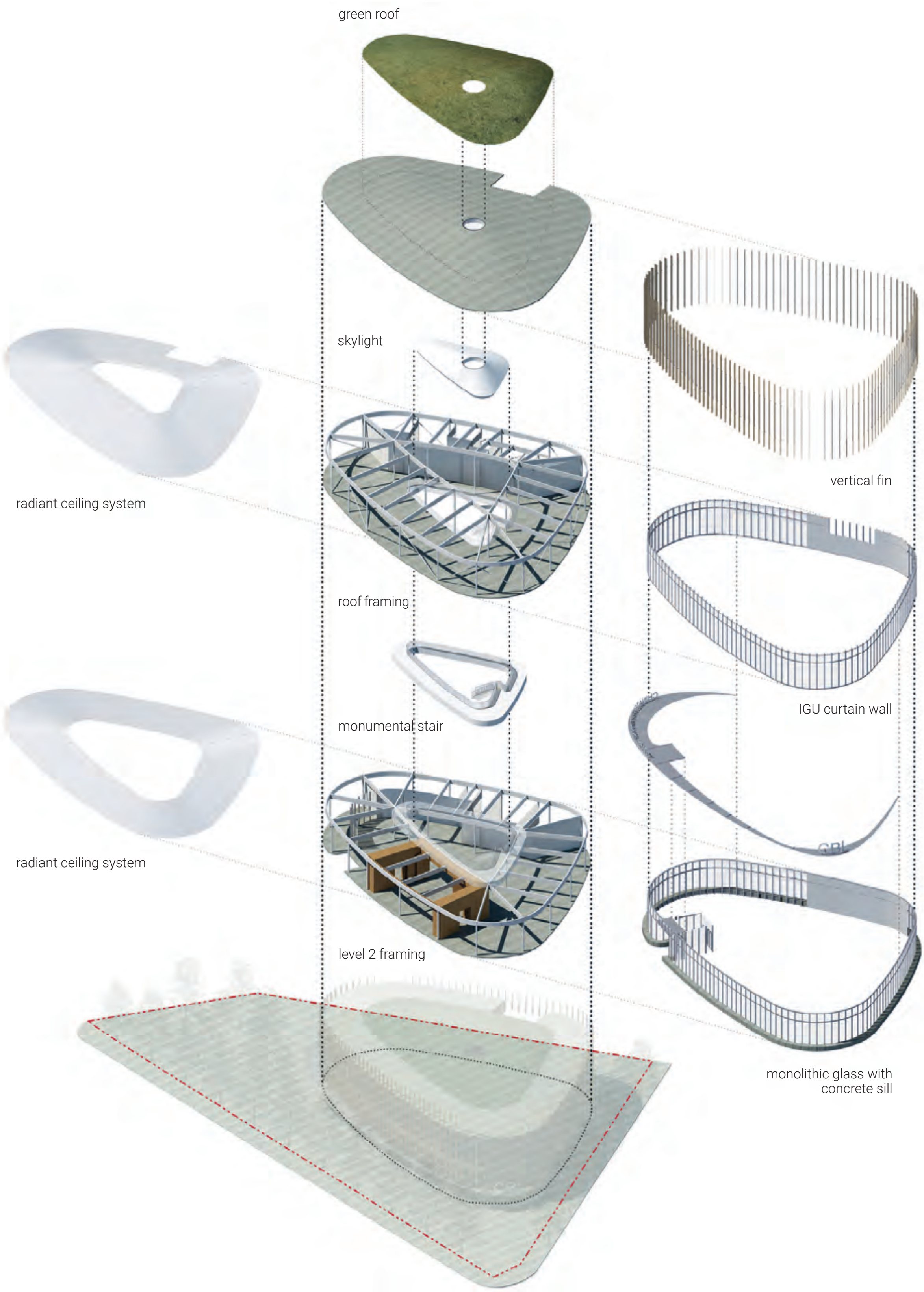


Figure 29
The outcome of the sensitivity analysis of the Embodied Carbon Assessment for the different life cycle stages


green roof
skylight
vertical fin
radiant ceiling system
roof framing
IGU curtain wall
monumental stair
radiant ceiling system
level 2 framing
monolithic glass with
concrete sill

In this case study, the building envelope accounts for between 40 and 50% of the total embodied carbon, depending on different assumptions. Therefore, it is necessary to specify the recycled content of steel and aluminium used for the calculation to make the assessment reliable and comparable.

To achieve informed decisions concerning the environmental impact of building materials, standardised calculation methods and reliable databases are not the only factors. There are practical challenges in data collection and the definition of the appropriate level of detail in the calculation, and the level of detail of characteristics and volumes of materials. Therefore, robust data management and extraction of project information are critical. The management of this information is fundamental to influence the design decisions early in the design process based on available data from previous projects or reliable databases.

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SEMI-AUTOMATED PROCESSES FROM BIM TO LCA

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According to the European Commission, European buildings account for 42% of final energy consumption, 35% of greenhouse gas emissions and 50% of materials produced in their production, use and dismantling [1]. Also, they are responsible for 30% of water consumption and a third of all waste [2]. These statistics demonstrate the need to identify and reduce the environmental, economic and social impacts of buildings through the use of calculation tools. In a discussion proposal for the new 'Building Energy Act' (GEG) from February 2018, the German Sustainable Building Council (DGNB) proposes that in the future, CO_2 emissions should be balanced rather than primary energy consumption [3]. This approach, which has been extended to include grey energy, is intended to create a goal-oriented, holistic approach.

In the following, the focus will be on the integration of life cycle assessments (LCA) into the building information modelling (BIM) process and their advantages and disadvantages in terms of achieving a regenerative design in practice. The major challenge is the semantic linking of the BIM model with the LCA model. BIM programs can be used to determine areas and masses automatically. The goal, however, is a fully automated LCA process that can be realised with the help of an integrated BIM and LCA model [4]. Therefore, in the first instance, a model analysis with different tools and workflows is investigated. In a second step, an optimised workflow is suggested by using a prototype with Autodesk Dynamo.

MODEL ANALYSIS OF BIM-INTEGRATED LCA WORKFLOWS

For the model analysis, 25 case studies were investigated. The author created BIM-models for each case study both in Autodesk Revit and ArchiCAD, which were exported as the open BIM exchange format Industry Foundation Class (IFC 2x3). To achieve a systematic and various model analysis considering the basic features of BIM models, the models are divided into two categories, one focusing on form, the other on material (see Table 1). The first category distinguishes between different floor plans, multi-storey buildings, orientations of slanted walls and roof geometry. The material category is differentiated by monolithic, multi-layered components as well as different types of wall structures, windows and doors, and roof structures.

The software eLCA was used according to the current calculation workflow. Díaz et al. [5] state that BIM-integration of LCA can be implemented through a semi-automated or fully automated workflow. The Revit plug-in Tally was used for the semi-automated work process using the native exchange format of Revit and IFC export of Revit and ArchiCAD imported to Revit for the model analysis. One Click LCA was used for the fully automated process (Figure 30) using the native exchange formats of Revit and ArchiCAD and their IFC export models imported to Revit, ArchiCAD and Simplebim.

The results show that even with simple models of the IFC files, from 200 LCA calculations based on IFC-exports 92 results had slight or strong deviations due to several reasons (Table 2). This result shows that the 'open BIM' approach has not been entirely developed yet for the fully automatic calculation of BIM-integrated LCAs. There were also problems with the correct material input with One Click LCA. This is because composite materials cannot be displayed correctly in the software export or import. Another primary reason is the missing transparency of component-specific materials allocation to add additional or missing layers at a later stage. The calculation with the LCA-program Tally was only possible based on the LCA method of LEED v4, and the data sets were optimised mainly for the American market. There is no interface for importing chosen EPDs or data from the Ökobaudat database.

In general, a more precise nomenclature of materials with a qualitative name suffix is recommended to guarantee a correct, component-specific material assignment. This can be the minimum compressive strength class for concrete, the wood species for timber or the type and processing method of metals.

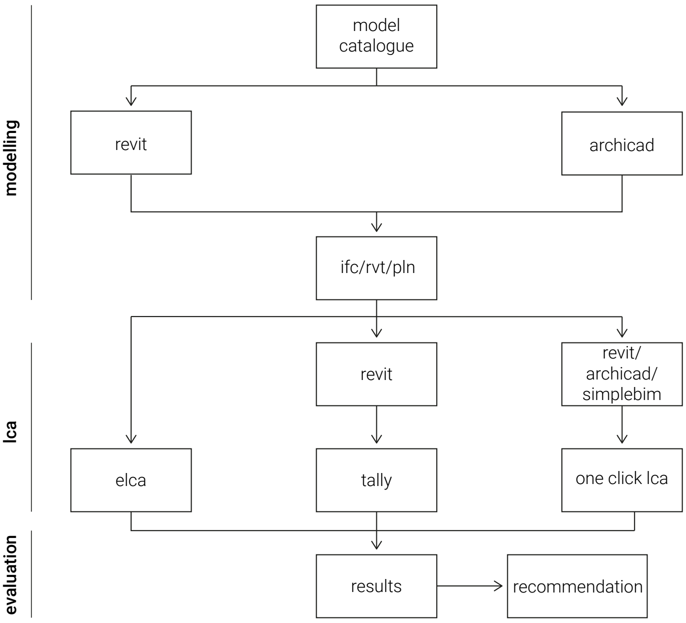
Table 1

Model catalogue for case studies of the model analysis, divided into the two main categories form and material

		modellgroup	case study	
form	f1	ground floor	angular	F1e
			round	F1r
	f2	multistorey	suspended ceiling	F2z
			gallery with columns	F2g
	f3	sloping walls	outside inclined straight wall	F3ag
			outside inclined round wall	F3ar
			inclined inside straight wall	F3ig
			inside inclined round wall	F3ir
	f4	roof	saddle roof	F4s
			saddle roof with corner	F4e
			hip roof	F4z
			pent roof	F4p
material	m1	monolithic	reinforced concrete	M1s
			brick wall	M1m
			timber	M1h
	m2	multi-layer	reinforce concrete + EPS	M2s
			brick wall + XPS	M2m
	m3	construction	mullion-transom facade	M3p
			wood frame construction	M3h
	m4	window/doors	wood frame	M4h
			aluminium frame	M4a
			plastic doors	M4k
	m5	roof	warm roof (flat)	M5s
			brick covering (saddle roof)	M5z
			sheet metal cover (pent roof)	M5b

Figure 30

The procedure of the model analysis of BIM-integrated LCA workflows, starting with the modelling part in Revit and ArchiCAD, followed by the LCA-calculation with LCA, Tally and One Click LCA and ending up with the evaluation of all results and derived recommendations



LCA-software	**Tally**			**One Click LCA**										
LCA-plugin-in	revit	revit	revit	revit	revit	revit	simplebim	simplebim	archicad	archicad	archicad			
file-format	RVT	IFC	IFC	RVT	IFC	IFC	IFC	IFC	IFC	IFC	PLN			
BIM software	revit	revit	archicad	revit	revit	archicad	revit	archicad	revit	archicad	archicad	●	◆	☐
F1e	●	●	●	●	●	●	●	●	●	●	●	11	0	0
F1r	●	●	●	●	●	●	◆	◆	●	●	●	9	2	0
F2z	●	●	●	●	●	●	●	●	●	●	●	11	0	0
F2g	●	◆	●	●	●	●	●	●	☐	●	●	9	1	1
F3ag	●	●	●	●	●	◆	☐	●	●	●	●	9	1	1
F3ar	●	☐	☐	●	☐	☐	☐	☐	●	●	●	5	0	6
F3ig	●	●	☐	●	☐	☐	☐	◆	●	●	●	6	1	4
F3ir	●	●	☐	●	☐	☐	☐	☐	●	●	●	6	0	5
F4s	●	☐	☐	●	●	☐	●	●	●	●	●	8	0	3
F4e	●	☐	☐	●	●	☐	●	◆	◆	●	●	6	2	3
F4z	●	☐	☐	●	●	☐	●	●	◆	●	●	7	1	3
F4p	●	☐	☐	●	●	☐	●	◆	●	◆	●	6	2	3
M1s	●	●	●	●	●	●	●	●	●	●	●	11	0	0
M1m	●	●	●	●	●	●	●	●	●	●	●	11	0	0
M1h	●	●	●	●	●	●	●	●	●	●	●	11	0	0
M2s	●	●	●	●	●	●	●	●	●	●	●	11	0	0
M2m	●	☐	●	●	☐	●	☐	◆	☐	●	●	6	1	4
M3p	●	☐	☐	☐	●	●	●	☐	●	●	●	7	0	4
M3h	●	◆	☐	●	●	☐	◆	◆	●	☐	●	5	3	3
M4h	●	◆	☐	●	☐	☐	☐	☐	●	◆	●	4	2	5
M4a	●	☐	☐	●	☐	☐	☐	☐	◆	●	☐	3	1	7
M4k	●	☐	☐	●	☐	☐	☐	☐	☐	●	●	4	0	7
M5s	●	●	●	●	●	◆	●	◆	●	●	●	9	2	0
M5z	●	☐	☐	●	☐	☐	◆	◆	☐	☐	●	3	2	6
M5b	●	☐	☐	●	☐	☐	◆	◆	☐	☐	●	3	2	6

●	25	11	11	24	16	10	13	10	17	20	24	181		
◆	0	3	0	0	0	2	4	9	3	2	0		23	
☐	0	11	14	1	9	13	8	6	5	3	1			71

Legend

● correct result

◆ slight deviation

☐ strong deviation

Table 2

Comparison of the results of the model analysis subdivided by the BIM Authoring Software, the exchange file-format, the software for LCA-Plug-In and the LCA Calculation Software

Although the promise of a fully automated LCA calculation sounds convincing, transparency and comprehensible adaptability suffer as a result. With an optimised BIM model, the results can achieve a high degree of accuracy. However, skipping the step of material allocation or its control would be negligent since in complex projects with many different component layers it often leads to considerable divergences. A check of the component-specific building materials for completeness and quantity is therefore highly recommended, as is precise post-processing of the material take-off through correction and additions of missing layers and materials.

Most errors occur during the software-independent export into the IFC file format. Also, the IFC imports in the individual BIM programs cause deviations in the geometry and material assignment. There are significant problems - and thus optimisation potential – when dealing with more complex geometries, such as sloping walls, window and door components and multi-layer roofs.

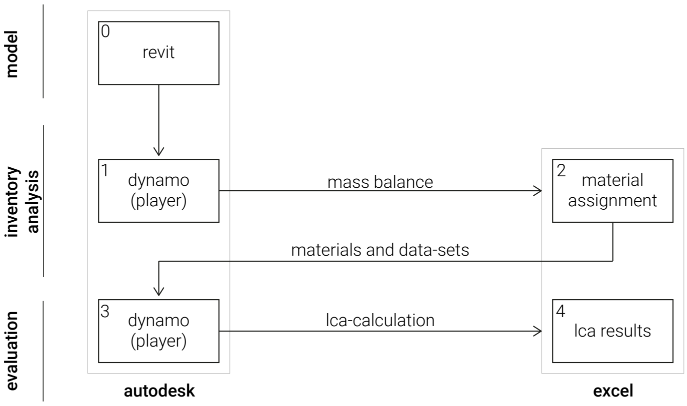


Figure 31

Prototypical approach for an optimised workflow using Autodesk Revit and Dynamo and Excel and structured by the LCA phases Inventory analysis and Impact assessment

IMPROVED WORKFLOW WITH A PROTOTYPICAL IMPLEMENTATION

The next step was to implement a prototypical LCA calculation tool using Autodesk Dynamo and Excel. The prototype solves the previously described problems by allocating component-specific materials and post-processing the material layers according to the specified component catalogue.

Tsikos and Negendahl [6] have already developed a method using Revit, Dynamo and Excel to calculate an LCA using an Integrated Dynamic Model (IDM). However, they aim to achieve a fully automated work process. Material allocation is carried out with the aid of a 'permanent link' between an external Excel database and the materials in Revit. Inaccuracies of the BIM model can be adjusted later in the model, but this way seems cumbersome, and a precise working method is not given. The present work is intended to make a specific contribution to optimising the compatibility between BIM models and LCA tools and to find a consistent and transparent calculation approach with a semi-automated workflow.

The aim is to enable complete transparency and the possibility to correct incomplete details in the LCA calculation process, in which the data for calculation and allocation are presented understandably. Adjustments for individual parameters can be made easily, quickly and precisely using Excel interfaces (Figure 31). These include changes to layer thicknesses, composite proportions, lifetimes or end-of-life scenarios for building materials. The prototype uses the LCA calculation method of the DGNB system [7]. All components relevant for the LCA calculation are recorded via Dynamo and exported to Excel. However, in some cases, there are still problems with the geometric export of stairs, windows, façade elements and beams. These problems can be corrected by manual post-processing in Excel. An assignment for composite materials and different end-of-life-scenarios was also implemented.

This approach, however, partly compromises the fully automated real-time calculation in order to achieve more precise results. Also, this interface is only intended for models in Revit, but this post-processing correction step can adjust models of faulty IFC files. Although the planned procedure is more cumbersome than the fully automated calculation, it can ensure a sufficient quality of the LCA with more precise results.

The prototype was validated by comparing its results with existing manual tools. For this purpose, the calculation method corresponds to the LCA calculation according to the DGNB system 2018 [7]. Fifty years were assumed as the service life of the building, and the database used for the LCA impact factors of the construction materials is Ökobaudat 2013. The error deviation of 1.13%, which occurred in the evaluation process of the prototype, is the result of more accurate mass determination through BIM integration.

In general, BIM-integrated LCA is very well suited for fast and straightforward operation. However, for correct calculation, precise modelling requirements and recommendations for the quality of the BIM model must be communicated to the architect and planners at the outset. Finally, a visual representation of the results is possible by using colour coding and Dynamo, although it is not implemented in the prototype yet. This enables a more intuitive and effective ecological optimisation of buildings. Interoperability between BIM and certification software must be further developed.

In addition to energy and ecological aspects, the LCA can also be completed by an assessment of the costs (Life Cycle Costing – LCC) taking the economic dimension into account. Further BIM-capable holistic sustainability criteria are available in the areas of socio-cultural and functional quality as well as technical quality.

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EVALUATING TOOLS COUPLING BIM AND LCA

Tiziano Dalla Mora and Fabio Peron *Iuav University of Venice, Italy*

This study aims to evaluate two LCA-BIM tools: Tally [1] and One Click, LCA™ [2] for Autodesk Revit [3]. Tally is a plugin for Revit software, developed by Kieran Timberlake and PE International that allows users to quantify the environmental impact of building materials for whole building analysis as well as to conduct comparative analyses of design options. The tally analysis accounts for the full cradle-to-grave life cycle according to the EN 15978 and utilises a custom-designed LCA database developed in GaBi 6 and using GaBi databases [4], consistent with LCA standards ISO 14040-14044.

One Click LCA, developed by Bionova, is an LCA and LCC (life cycle costing) software that allows users to create Environmental Product Declarations (EPD) for building materials as well as whole-building LCA, and to earn certification credits for a range of systems (e.g. BREEAM, LEED). The tool works as a plugin by importing data from Revit or BIM models, energy performance models, Excel, or via manual import. The tool is also third-party verified for EN 15978, ISO 21931-1, ISO 21929-1 and for input data for ISO 14040/44 and EN 15804 standards. One Click LCA provides access to its database for generic construction materials and a comprehensive list of available databases.

The *interoperability* between LCA tools and BIM software was investigated. In particular, the study compared the functionality of the two tools and focused on the integration in the design process in terms of their graphical interface, calculation, use of the specific database, selection material and the type of generated final report. Both Tally and One Click LCA allow for the investigation of the direct impact of each material to identify which ones cause the highest environmental impact in any given category.

The *identification of materials* is the most important stage in the plugin use: it concerns applying a correspondence between the design data inserted in the BIM model and the materials or components in the LCA tool: in practice, the user has to find materials in the LCA database with the same (or similar) characteristics described in the BIM model, for example, density, country, data source, typology, service life. So, it depends on the database quality, availability, congruence of information and the presence of specific products.

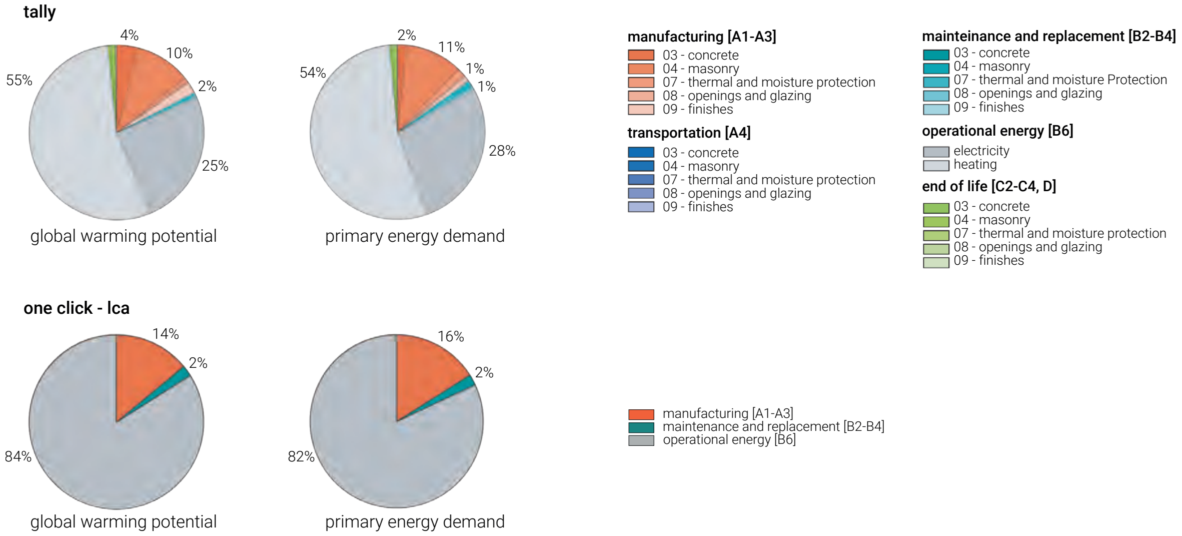

Figure 32

Environmental impact by Tally (top) and One Click LCA (bottom) calculation for masonry building. The software reports the calculation results of impacts such as Global Warming Potential and Primary Energy Demand. A chart describes the impact weighting of each Life Cycle Stage

The quantity of available materials in Tally is limited, and intended to represent the United States region and the year 2013, and thereby may not apply to other parts of the world. However, the Tally interface presents an organised structure, easy research filters, and it presents a very detailed characterisation of materials (thermal properties, density, take-off method, service life). One Click LCA presents a richer list of products and environmental labels, providing a comprehensive coverage of existing EPD databases, and also a more structured database with a filter area to define the search and the allocation of the material. However, the characterisation of products is not very detailed and exhaustive in the graphical interface, although the EPD or technical data sheet containing all details are available to download for most products.

Moreover, Tally and One Click LCA present different materials selection and calculations; while One Click LCA considers all products separately based on their EPD's, in Tally the default procedure gives the possibility to choose how to view a component. For example, a masonry wall could be treated as a single whole impact or as a sum of different layers, so the mortar and the finishing are considered as distinct materials.

In One Click LCA, the process of assignment of materials requires the quantity take-off to be reloaded into the cloud for each change in the BIM model. In contrast, Tally is a Revit add-in, strictly linked to the information of the model, and as such changes to the BIM model are seamlessly integrated into Tally.

In Tally, the user can define relationships between BIM elements and construction materials from the database while working on a Revit model. This results in an LCA on demand, giving a critical layer of decision-making information within the same time frame, pace and environment that building designs are generated. One Click LCA works with structural and architectural models and can adapt to material labelling practices. The cloud service to which the plugin connects detects the materials used in the model and calculates the environmental impacts automatically.

In both tools, the results of calculations are given in detailed reports, spreadsheet files, or graphical dashboards that provide a summary of all energy, construction, transportation, and material inputs of the assessment. The results of an LCA conducted on a masonry building are presented in Figure 32 and Figure 33. In particular, One Click LCA can be used for and complies with the different schemes, standards and requirements such as LEED, BREEAM, DGNB and Green Star, while in Tally a user guide is available to calculate the requirements of the rating systems.

In general, both tools have the potential to be very useful to determine the building's environmental impacts in the design process. Tally is very coherent with the BIM model, is more direct and is very helpful, especially in the early stage when the user generally considers different design options, materials, components and kind of structure. However, its focus on the North American market risks users based in other areas drawing wrong conclusions based on geographical differences. One Click LCA, in contrast, provides a wide range of EPD databases and also reports the results according to the requirements of the majority of environmental rating systems.

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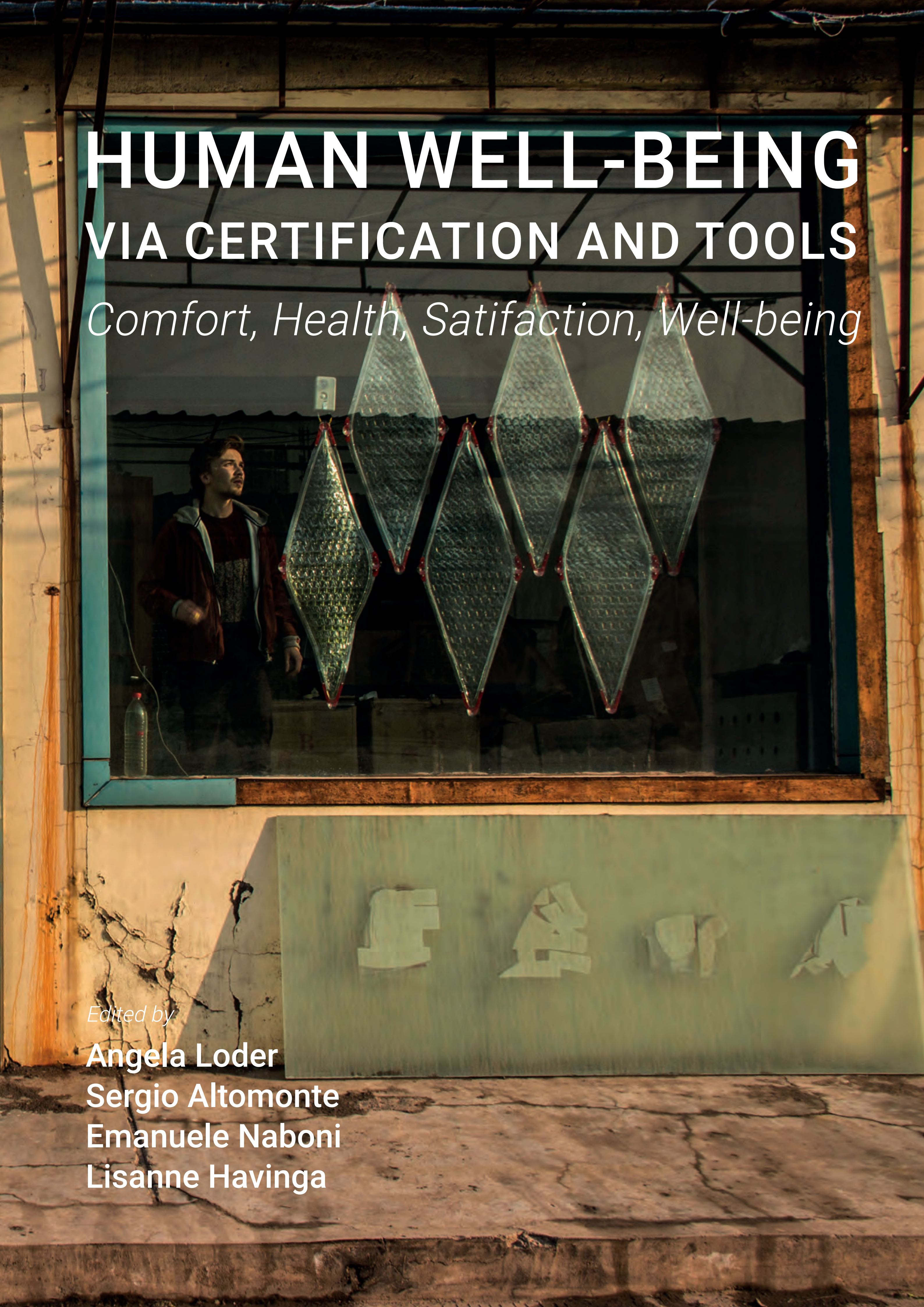

HUMAN WELL-BEING
VIA CERTIFICATION AND TOOLS

Comfort, Health, Satifaction, Well-being

Edited by

Angela Loder
Sergio Altomonte
Emanuele Naboni
Lisanne Havinga

Chapter Cover Image - Algae combat Air Pollution

Device testing how local algae could be integrated within facade systems to absorb air pollutants. The device was developed as part of the master program of 'Architecture and Extreme Environments' of he Royal Danish Academy. The device was developed and tested in the Gobi Desert in China to respond to local air pollution, which is heavily compromising people's health. Air pumped through cultures containing algae had significantly increased air quality and cut both hazardous gas and particle content. The system was probed as an urban skin for outdoor and indoor spaces.

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HUMAN WELL-BEING
VIA CERTIFICATION AND TOOLS

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PROMOTING HUMAN HEALTH AND WELL-BEING IN BUILDINGS

Angela Loder *International WELL Building Institute (WELL), United States*
Sergio Altomonte *University of Louvain (UCL), Belgium*

Despite being a common goal for many building standards and green-rating systems, a comprehensive framework to design, implement, and evaluate buildings for occupant health and well-being outcomes is yet to be achieved. Such a framework is required in order to provide a clear understanding of what health and well-being actually mean in buildings. It would provide a clear blueprint/strategy detailing/outlining/advising how to translate this understanding into building-level design, operations, and maintenance interventions, and a clear map of what metrics and tools are available (or need to be developed) to effectively measure and evaluate health and well-being outcomes.

For example, there is a common perception – at least in the general press – that green-certified buildings reduce impacts on the environment and create better spaces for their users, thereby enhancing their comfort, satisfaction and health. Although some studies have supported these tendencies in terms of energy performance [1] [2], the empirical evidence collected has been challenging to substantiate consistently [3] [4] [5]. Similarly, despite some research that has suggested improved measured and perceived indoor environmental qualities in green buildings, and direct benefits to human health and cognitive functions [6], a significant limitation of many studies has been their reliance on indirect and subjective metrics [7].

In fact, while improved environmental qualities and fewer health symptoms might have been detected after moving to green-rated buildings [8], research has also emphasised that self-assessed health can be driven by both physiological and psychological pathways [9]. Furthermore, environmental perceptions may, at times, be misaligned with actual environmental conditions [10]. This is, however, not surprising. By and large, high-performing and green-certified buildings have traditionally focused their design drivers on efficiency in terms of energy management, siting, water, resources, and the physical qualities of their indoor environment.

Nevertheless, based on the increasing recognition of possible adverse health outcomes from an environmental-only focus in buildings [11], attention has recently started to progress from limiting impacts to the environment – the traditional sustainability agenda – to restoring social and ecological systems to a healthy state (a restorative approach) and to make them actually evolve (regenerative design) [12]. This chapter provides a number of contributions that can help delineate a design framework in support of this change in approach.

Responding to the need to provide practical guidance to designers and building managers wishing to incorporate health, well-being and regenerative principles into their designs, many rating systems, such as LEED [13], BREEAM [14], Green Mark [15], the Living Building Challenge [16], etc. have recently started to include new credits and criteria in their schemes. Going even further, the WELL Building Standard™ [17] has been developed with a specific focus on the health outcomes of design, policy, and operational decisions in buildings, requiring the ongoing evaluation of both environmental performance and human experience. Lastly, there has been a flurry of technology and data developments that have given designers new tools for measuring and modelling outcomes, although they raise questions about when, where, and to whom they should be applied.

These developments mean that designers have both more options and also need more clarity on how to set health goals, how to measure them, and what tools to use in designing healthy, ideally regenerative, buildings. In this context, a debate is emerging on how biometrics, wearables and human data may be implemented in the design process. The proliferation of mobile health sensors and families of indicators measuring indoor environmental quality can help us understand the influences on health outcomes (e.g., ventilation, VOCs, particles). They also potentially enhance our ability to obtain direct and indirect measures of the health and well-being of building occupants. However, determining what sensors might best capture – or, more likely, reliably estimate (e.g., generating data on physiological states) – the health and the perception of an occupant in a building after construction is still a significant challenge.

THEORY AND DEFINITIONS

The first section of this chapter outlines some key theoretical and paradigmatic principles for framing health and well-being in buildings. Angela Loder offers an overview of traditional attitudes to health and the environment from a public health perspective and illustrates how this framework influences current approaches to health in buildings and even our understanding of health itself.

Finally, she provides a sample tool for designers to set health goals and evaluate the outcomes in a design project. As an addition to this theoretical piece, Szabina Varnagy discusses the opportunities and experiences of working with WELL certification from the perspective of a consultancy firm. Sergio Altomonte investigates the need for a new paradigm where the terms of comfort, satisfaction, health and well-being are ascribed a precise domain of interest and application, outlining some of the avenues of research investigation and design practices that can contribute to the achievement of a more comfortable, healthy and, ultimately, regenerative built environment.

CASE STUDIES AND EXAMPLES

The second section provides some case studies and examples of designing for health. Terri Peters introduces issues related to evidence-based design and explains how this should inform decisions from the beginning, reinforcing the business and environmental case for regenerative design. To this end, her contribution presents examples of 'superarchitecture', i.e. buildings designed to be net positive in their strategies for the promotion of health and environmental sustainability, blending regenerative and health design goals.

CERTIFICATION AND DATA COLLECTION TECHNOLOGIES

The last section addresses this need for more guidance around technologies and data-collection metrics and tools that can aid designers in creating healthier buildings. James Connelly presents an ingredient's label for building products that was developed to promote a greener, healthier environment for construction workers, building occupants, and consumers alike. Rick Kramer and his colleagues offers some insights into state-of-the-art laboratory facilities and measurement tools for field studies, elaborating on the shift from static to dynamic indoor environments and how this can affect physiological health and thermal comfort. Hugo Silva illustrates progress in the field of wearables and biomedical sensing. The contribution presents several practical examples of tools and conceptual installations that illustrate how the architectural space of the future is able to become an 'invisible doctor' supporting health services for building occupants (e.g., assessing comfort and health, facilitating preventive healthcare, creating healing environments, etc.). Lastly, Emanuele Naboni and his team present a series of innovative and creative devices that are aimed at measuring and/or cleaning air in regions impacted by air pollution. The devices were developed and tested in the Gobi Desert in China.

CONCLUSION

Whereas the other chapters offer an overview of simulation tools and assessment methods, this chapter has a stronger focus on the generation of measured data. Although certain indicators related to health and well-being can be simulated, a holistic tool to predict well-being outcomes effectively is yet to be developed. This is partly because definitions, metrics, and methods are still evolving. There are some promising developments in the field of modelling well-being, but qualitative studies and surveys remain essential as there are no digital tools yet that negate the need for individual human analysis and evaluation.

The promotion of human health and well-being in buildings should move from a risk-to-health perspective towards a more holistic salutogenic model of health-promotion. It is this holistic attitude to health and well-being in buildings that offers the most promise for overlap with a regenerative design approach, both of which encourage health and quality of life. After all, if we hold to the belief that *'we shape our buildings, and afterwards our buildings shape us'* [18], designing and operating them towards human health and well-being outcomes might be in the very best interests of us all.

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IMPLEMENTING AND EVALUATING PUBLIC HEALTH GOALS IN BUILDINGS

Angela Loder *International WELL Building Institute (WELL), United States*

The focus on regenerative design, both at a community and a building level, has renewed interest in what healthy buildings, communities and ecosystems look like. However, many of the models for a healthy building are based on ecosystem services or indoor environmental quality work in building sciences, and focus mainly on a risk-reduction approach to health. This focus ignores the more socio-ecological approach used by public health and can dismiss health-promoting design features as ‘nice to have’ but not linked to ‘real health’. This lack of understanding of health, and how building level interventions can impact health outcomes, means that designers often lack the tools and language to talk to building owners about the value of health-focused interventions, or know how to set health goals and evaluate them. This contribution gives an overview of traditional approaches to health and the environment from a public health perspective, explains how this framework influences current differences in health terms (such as wellness vs well-being), and gives a sample tool for designers to use to set health goals and evaluate the outcomes in a design project.

REGENERATIVE DESIGN AND HEALTHY BUILDINGS: AN EVOLVING RELATIONSHIP

Many of the models that come from ecosystem services consider a risk reduction approach to health, *e.g.* the reduction in flooding and heat stress from better designed infrastructure [1]. Similarly, at a building level, experience from adverse health outcomes, such as sick building syndrome from energy-efficient buildings in the 1970s [2], has meant that for many, a healthy building is most likely a ‘green’ building; it reduces risks to health, usually through better air quality and improved thermal, acoustical, and lighting comfort [3]. There is also some general understanding, based on popular perception and recent media coverage of easy-to-digest research [4], that access to nature also provides health benefits [5], though how this fits into a risk reduction, building science approach, is not always clear.

Finally, there are numerous apps and digital modelling advancements that aim to track health-related behaviours (such as step counters and sleep monitors), or the interface between user perceptions of comfort and indoor environmental quality parameters, thus providing designers more tools to address human experience in buildings [6-8].

However, when asked to design or to set health goals for a healthy building many designers are at a loss on how to understand, define and measure health and well-being, identify what design strategies will be most effective, and appropriately evaluate the outcomes. These are not merely academic dilemmas; backing up health claims, and the often-higher capital cost that comes with a regenerative or healthy building, requires some evidence of a return on investment for most developers, or at the very least evidence that links the proposed intervention with measurable health outcomes. Below is a short discussion that can help designers to: a) explore how public health has understood the links between the environment, including buildings, and health outcomes; b) understand what we mean by health, well-being and wellness; and, c) use an example of how to set health goals and link them to building-level interventions and public health outcomes.

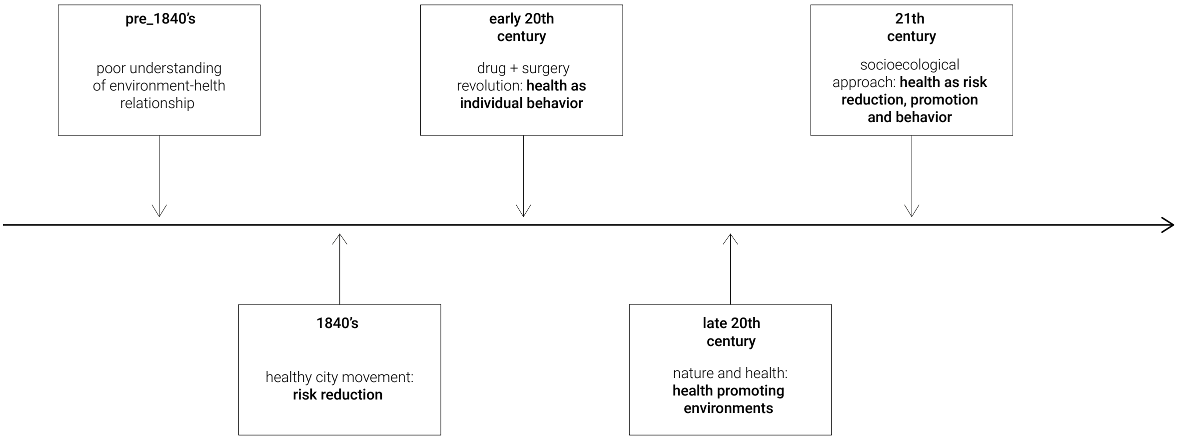


Figure 1
This timeline illustrates the different approaches that the discipline of public health has taken towards health and the environment. This approach has moved from a risk-reduction approach to a health-promotion and individual action, to environment as healing or health-promoting, to the current socio-ecological approach favoured by many public health agencies when dealing with complex issues such as encouraging physical activity.

PUBLIC HEALTH AND THE ENVIRONMENT: A SHIFTING APPROACH

Public health has recognised the impact of the environment on our health since the mid-1800s with the beginning of the Victorian Sanitation and Healthy Cities Movement [9, 10], mostly from a *Risk Reduction* approach (see Figure 1). Key figures such as Dr John Snow in London realised that the environment - in this case, the quality of drinking water up or downstream from a pipe dumping raw sewage into the Thames - had a direct impact on public health. In the early 20th century, advances in drugs and surgery led to the *Health as an Individual Behaviour* approach, and the role of the environment on health faded into the background. Health outcomes here were viewed primarily as a function of individual lifestyle choices - such as eating well and exercising - and not connected to the larger environment as a whole [11].

In the U.S., U.K. and northern Europe in the 1980s, researchers began to challenge the idea that the impact of the environment on health was *only* negative, or that health outcomes were only the result of individual lifestyle choices. Research began on the role that some natural landscapes had on positive health outcomes, or a *Health-Promoting Environment* approach [12, 13]. This can be seen in research that looks at the health benefits of access to nature at both a landscape and building scale [14, 15]. Designers will be familiar with this work mostly through biophilic design [16]. Lastly, public health began to realize that simply exhorting people to eat right and exercise more was not very useful when there were numerous barriers to doing so, such as a lack of safe, convenient routes to walk to work, school and home, or a lack of appealing places to go in the first place. This is called a *Socio-Ecological* approach, and is a combination of the first three approaches [17]. Walkable streets, healthy eating, and active living initiatives are community-level examples of this approach in action [18].

At a building scale, this means understanding that the design, policy, and maintenance and operations choices have health and well-being outcomes that should be made visible and measurable. The WELL Building Standard™ uses such a socio-ecological approach and views the building as a public health intervention tool through both active (meaning the user is encouraged to make a healthy behaviour choice, such as using the stairs), and passive (*e.g.* better access to daylight or good air quality) options [19]. Unlike workplace wellness programs, all users can benefit from a healthy building simply by being in them.

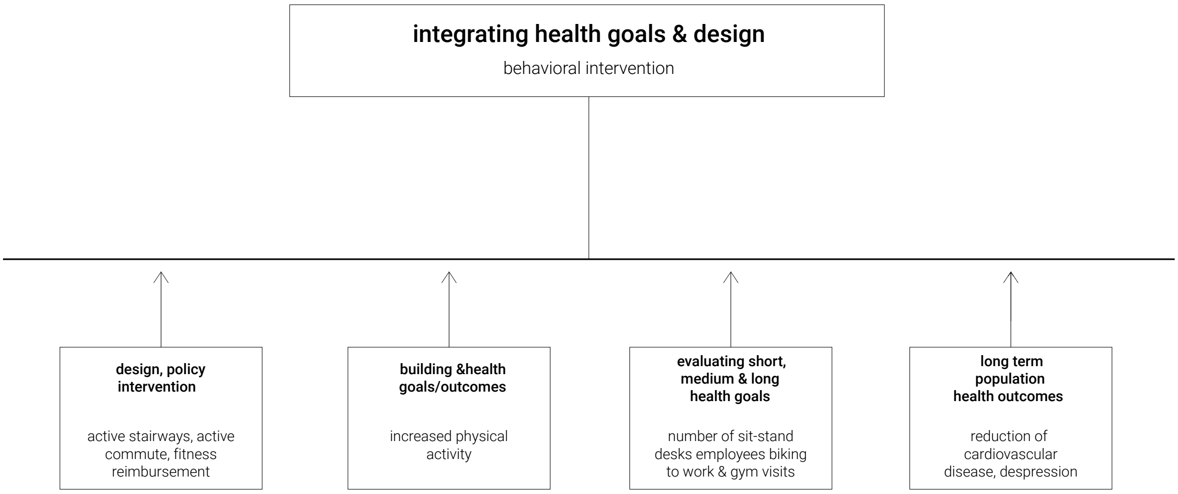
WHY DOES THIS MATTER?

Understanding how the field of public health has traditionally thought about buildings matters because projects may encounter all of the above viewpoints on health and buildings through building managers, owners and occupants. Some may think that all that is needed for a healthy building is to ensure good indoor environmental quality (a Risk Reduction approach), that they should not be responsible for encouraging healthy behaviour since it is all about individual choices (Health as Individual Behaviour), or that providing health-enhancing environments (Health-Promoting Environment approach) is nice to have but not of 'real' value. Understanding the possible attitudes and values of clients around health and buildings will help designers craft the right message to help them see the value in a holistic approach.

HEALTH, WELL-BEING AND WELLNESS IN CONTEXT

This background should help designers understand more clearly why there is a difference between various definitions of health and why these differences matter. For example, the World Health Organization's classic definition of health – *'a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity'* [20] - uses a socio-ecological approach, not a risk reduction approach, that covers all evidence-based determinants, or influences, on health. Well-being, while sometimes seen as 'less real' because it depends on a person's subjective experience, is in fact linked directly to measurable health outcomes, and is an essential component of good health.

Figure 2
This image shows how designers might approach adding health goals to their project. Designers should begin with the health goals and desired outcomes, move backwards to decide which intervention will help them achieve those outcomes, and then move forwards to list different methods to evaluate these outcomes and link them to long-term public health outcomes, as applicable.



This also means that while apps and big data are providing many exciting possibilities for measuring some aspects of health, they are not adequate by themselves to capture the full spectrum of human health, well-being and experience, which requires expertise in survey development and analysis. Lastly, wellness, while often used interchangeably with well-being, refers more to the awareness of, and lifestyle choices, of an individual [21]. While companies can aim to create a 'culture of wellness' through education and programming, researchers need to focus on health and well-being outcomes that are effectively measurable.

HOW TO SET HEALTH GOALS IN A PROJECT

The image below (Figure 2) represents a model that designers can use to set health goals, identify which interventions, or actions, to use to achieve the desired health outcome, some ways to evaluate these outcomes, and, where possible, how to link these to more substantial public health outcomes.

Figure 2 showcases an active health goal, *i.e.* a desired change in occupant behaviour. Here we have chosen a commonly understood goal – increased physical activity – which we know is linked to better health outcomes. Moving backwards, a designer can choose design and policy interventions that have been shown to increase rates of physical activity, such as active stairways (design), or fitness reimbursements (policy). Moving to the right, designers can then evaluate measurable outcomes to see if their intervention is working, such as the number of employees biking to work, using the stairs, or going to the gym.

These can be measured both in the short term, such as within three months of the intervention, and long-term, such as a year after the intervention, to evaluate changes in health behaviour. Lastly, increases in physical activity are linked to population-level health outcomes such as the reduction of cardiovascular disease and depression. While not measurable at a building scale, linking to these larger public health outcomes can help projects and owners understand the potential longer-term impact of building-level interventions, and how their project may address top health issues in their region.

These tools can help designers to better understand how health and well-being goals can be incorporated into a building, communicated to project owners, and evaluated for their possible health outcomes, which will continue to provide evidence on the effectiveness of these health interventions.

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WELL-BEING IN PRACTICE

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This section lays out the experiences of ABUD, a consultancy firm specialised in sustainable building and urban design in Budapest. ABUD is, at the time of writing, consulting for the WELL [3] certification of six office building developments in Budapest, Hungary. The projects range from 9 000 to 34 000 m^2. The owners are aiming for WELL Core and Shell certification, which addresses the building structure, window locations and glazing, building proportions, heating, cooling and ventilation systems, and water quality. Figure 3 shows how different disciplines and experts are involved throughout the WELL certification process at ABUD. Not only architects, designers and engineers are involved, but there is a strong emphasis on those involved with procurement, operations and maintenance, and building policies. WELL works harmoniously with the BREEAM [1] and LEED [2] building rating systems. When used in parallel, this ensures that buildings meet global goals of preserving energy and resources for a more equitable future, and local goals of enhancing human health, well-being and work performance.

During the consultancy of WELL certification digital simulations were used, in particular when it comes to daylight analyses. In the concept phase, daylight factors were calculated, and during the detailed design phases, more advanced simulations were carried out. Daylight glare probability (DGP), spatial daylight autonomy (sDA) and annual sunlight exposure (ASE) helped determine the optimal window-wall ratio, type of shading, schedules of shading control and glazing parameters.

Some of the insights that emerged from these experiences of consulting for WELL certification are related to requirements for water quality, urban food production and biophilia. WELL has demanding requirements for water quality, with almost 40 components to be analysed. Drinking water needed to be tested at several locations in Budapest, showing that the water is of high quality. Another insight was that the developers were open to community gardening solutions. These are spreading around the city, and several office buildings are today suitable for food production. Some of the WELL requirements were already at the core of the architectural design. For instance, the architects integrated quality views and access to nature, natural daylight provision and biophilic design elements.

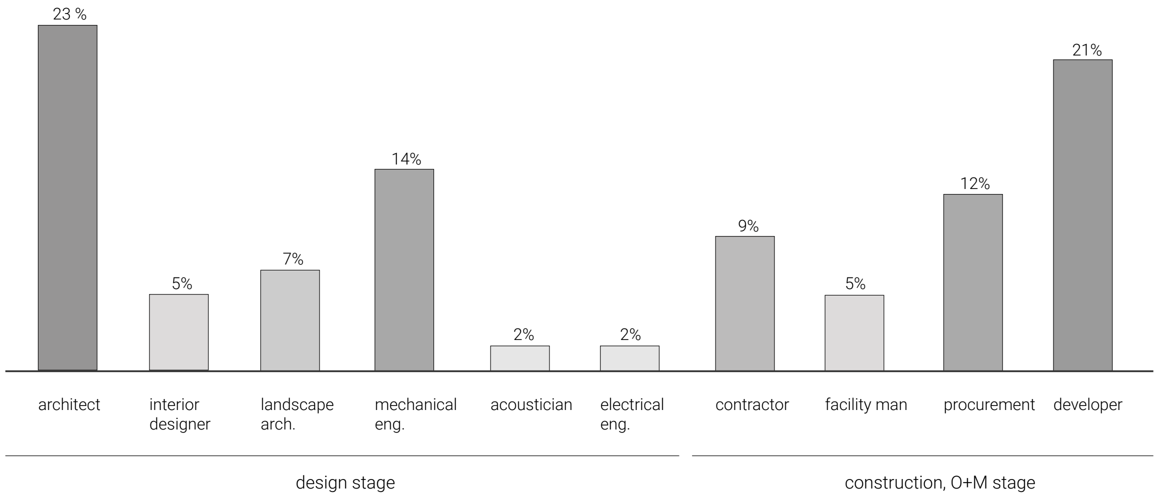

Figure 3

Breakdown of responsibilities throughout the certification process at ABUD, showing the different disciplines and experts involved throughout the WELL certification process.

There were some contextual difficulties throughout the process of WELL certification. These were, for example, translating some of the WELL requirements into the Central-East-European construction environment, like procuring materials for the VOC requirements. The health effects of building materials have not been a significant concern for Hungarian architects and developers. Selecting the right materials was thus a lengthy process, which involved laborious research and caused an unexpected increase in construction costs. A further difficulty was that the national building code does not set any strict requirements that ensure access to the built environment for people with disabilities such as those set by international standards like the ADA Standards for Accessible Design [4]. Surprisingly, the importance of the latter had to be emphasised repeatedly to the whole project team, as accessibility principles have been applied only loosely in the past in Hungary in the misguided belief that the solutions used so far are enough to create an equitable environment.

As a conclusion, developers, architects and engineers who consider sustainability to be important tend to be open to regenerative design goals and to design that promotes health. Regenerative design and design for health can be achieved without pursuing any building certification system. However, certification systems support these processes and help to crystallise a set of data that can be compared with future post-occupancy evaluations (POE). The lessons learned can be transferred to further projects, disseminating knowledge, principles and solutions.

It is finally noted that what is deterring most builders from considering the principles of regenerative design and design for health are the – often only perceived – high initial costs, and lack of knowledge of solutions beyond the current, widely used practices. The importance of awareness-raising and dissemination cannot be emphasised enough. Research that quantifies the built environment's effects on human health and well-being can significantly facilitate the cooperation between construction industry stakeholders, manufacturers, policymakers and the building users by highlighting the impact and significance of required interventions.

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DEFINING COMFORT, SATISFACTION, HEALTH AND WELL-BEING

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Comfort, satisfaction, health, and well-being are recurring terms in today's' scientific research and design practice in the field of the built environment. However, within the pressing agendas driven by priorities of energy-efficiency and sustainability, they are often used almost interchangeably and are seldom ascribed a precise meaning. Instead of attempting the unlikely definition of a comprehensive new inter-disciplinary framework that can address the complexity associated with these notions, this paper aims to investigate the different boundaries of application of each of the above terms. In so doing, it outlines some of the avenues of research enquiry and design practice that can contribute to achieving a more comfortable, healthy, sustainable and, ultimately, regenerative built environment.

Growing concerns about the need to curb greenhouse gas emissions, and awareness that buildings cause around 40% of global energy consumptions [1], have been pushing energy efficiency to the forefront of the sustainability agenda in the construction industry. Yet, '*buildings don't use energy: people do!*' [2]. Occupants greatly influence the energy use of buildings through interactions with environmental controls and their physical, physiological and/or psychological adjustments. However, one of the causes of the *performance gap* that is often detected between simulated and measured energy use relates to the yet incomplete prediction and characterisation of users' responses to changes in environmental stimuli [3].

Since people spend almost 90% of their time indoors [4], substantial research has investigated the conditions that drive perceptions and the actions that occupants take to meet expectations of *comfort* and *satisfaction*. These behaviours (e.g., opening a window, drawing a blind, switching on/off artificial lights, setting a thermostat, etc.) are generally assumed also to be beneficial to *health* and *well-being*. Nevertheless, even if these targets – comfort, satisfaction, health and wellbeing – are correlated with each other, they lead to different implications.

IN SEARCH FOR DEFINITIONS

Comfort can be defined as a '*physical and material state*' that is '*pleasing or grateful to the senses*' [5]. Many physical factors can influence comfort in buildings: temperature, sound, odours, and lighting present in a space. These are commonly encapsulated under the banner of 'IEQ' or *indoor environmental qualities* [6]. A large body of research shows that inadequate IEQ can affect the perception of comfort and result in negative consequences, for example, on job performance [7] [8]. Yet, design practices might not yet be suitably informed by a complete appreciation of how IEQ conditions might support comfort, and enhance or impair occupant satisfaction [9] [10] [11].

Rather than simply being influenced by quantifiable physical factors, in fact, *satisfaction* implies a '*state of mind*' that is driven by gratification from '*a need or desire as it affects or motivates behaviour*' [5]. People have intrinsically different preferences, and their responses depend on many variables [12] [13]. Sensory inputs, also, are not processed independently by the nervous system but, rather, interact with one another in multisensory integration. The satisfaction resulting from environmental exposures, therefore, is a composite state involving an overall response to a combination of stimuli that includes, other than objective physical factors, also subjective physiological and psychological dimensions.

It is in this context that we need to frame the more comprehensive World Health Organisation's definition of *health* as going beyond '*merely the absence of disease or infirmity*' [14]. This definition is particularly important today at a time of greater understanding of the risks of unhealthy lifestyles, medical and technological innovations, the demands of an ageing population, etc. Although there is an established body of quantitative evidence related to the study of physical health in indoor environments [15], research into *well-being* – an even wider and overarching construct of physical, physiological, and mental aspects combining *hedonic* and *eudemonic* dimensions, i.e. feeling good and functioning well [16] – is relatively recent. Current research in buildings focusing on well-being is shifting from purely epidemiological considerations (i.e., risk reduction, sick building syndrome, etc.) towards a more holistic and inter-disciplinary appreciation of the multi-dimensional connections between the built environment and their human dwellers, of which comfort and satisfaction are only a part.

RESEARCH AND DESIGN FOR HEALTHY AND REGENERATIVE BUILDINGS

Although various design criteria have been developed and included in standards and regulations towards the comfort, satisfaction, health and well-being of building occupants, research shows that several characteristics of today's indoor environments can still present a threat to building users [17]. This is primarily because many objective and subjective relationships (i.e., dose-response) between environmental factors and human reactions have not yet been fully understood. This still demands significant investment in experimental research. Until now, the development of indices and models has mostly focused on steady-state conditions without considering the dynamics of a real-world environment [15]. In addition, most studies have concentrated on individual factors, without considering multi-layered interactions between parameters. Lastly, most research has not considered (or distinguished between) inter-individual variability (differences between building users) and intra-individual variability (different responses were given by the same user, e.g. at different times or circumstances) [18].

Most standards and regulations effectively acknowledge that '*individual differences in perception and subjective evaluation*' might result in '*some dissatisfaction*' [19]. However, under the banner of energy efficiency, current design practices still mostly aim at '*minimising dissatisfaction as far as is reasonably practicable*' [19] by the creation of neutrally acceptable conditions. Such 'uniform' environments, nonetheless, may effectively jeopardise occupants' comfort, satisfaction, health and well-being by limiting exposure to dynamic stimulation that, at a specific dosage, times of the day, combination, season, etc., could have a positive influence on their physical, physiological and psychological requirements.

As an example, solar ingress in buildings in the morning hours, particularly in a cold season, might bring valuable passive heating and also decrease energy use for artificial lighting. However, especially in an office space, direct bright sunlight could cause glare and reduce visual comfort and hinder task performance. Moreover, yet, exposure to morning light, due to its spectrum and temporal occurrence along the daily circadian cycle, can favour the entrainment of the metabolic system with significant benefits for the biological welfare of the individual. This is just one example supporting the assumption that there might actually be significantly large discrepancies between a building's efficiency requirements (energy), what users demand to perform their activities (comfort), what drives their desires and wishes (satisfaction), and what they need to feel well (in the short and medium term) and be healthy (in the long term).

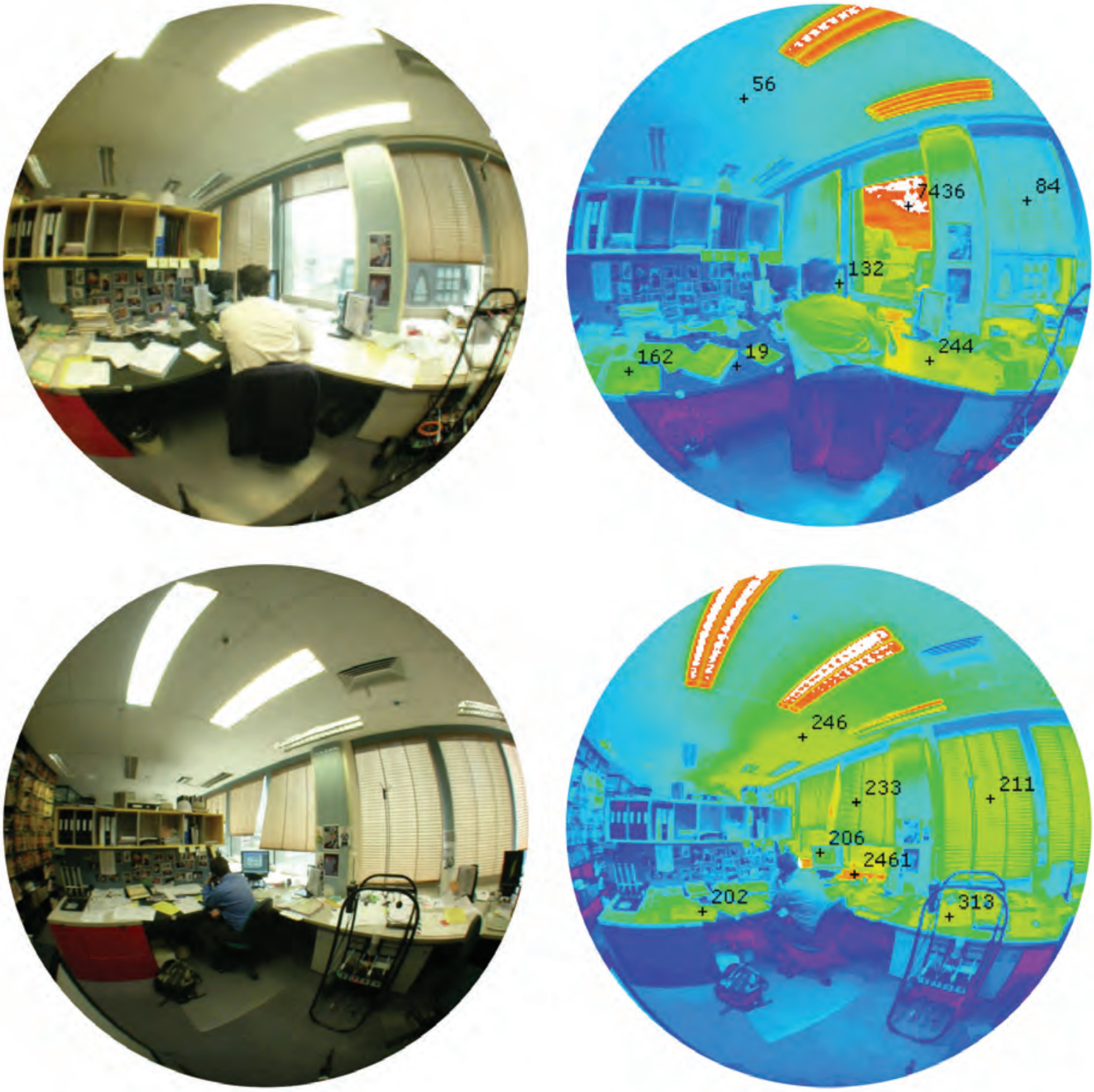

Figure 4

Fish-eye lens (left) and luminance mapping (right) of lighting conditions in an office during winter (top) and summer (bottom). Responses to the risk of discomfort due to glare show seasonal variability that might be independent from physical parameters.

Figure 4, for example, shows luminance mapping taken in an east-facing office during the early morning hours of winter (top) and summer (bottom). In these Post-Occupancy evaluations (POE), occupant behaviour (i.e., drawing the blinds) differed between seasons, although internal IEQ conditions, visual tasks and activities and time of day were essentially the same. This was not driven by visual comfort demands (i.e., avoidance of glare), but rather by the need to feel refreshed by the presence of sunshine during dark winter months.

This shows the urgent need to thoroughly investigate the complex effects of indoor environmental qualities on buildings and their occupants, and to transfer this new knowledge into research and design practice. Regenerative sustainability requires exceeding the traditional environmental, social, and financial requirements framed by established paradigms and the metrics conventionally used to benchmark them.

However, of course, there can be no ‘magic weapon’ to respond to these questions. Given the dynamic and evolving nature of buildings, the complexity and diversity of their users, and the importance for these variables to be comprehensively balanced in the design and operation of the built environment, there are still many challenges that need to be tackled [20]. Nevertheless, as shown by the substantial recent advances in research, design and regulations, sustained efforts in academia and practice can surely offer significant opportunities to work towards the realisation of better, more comfortable, higher performing, healthier, and ultimately regenerative buildings.

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SUPERARCHITECTURE: DESIGN FOR HEALTH

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'As an architect, your everyday decisions, large and small, can affect the mental and physical health of everyone that comes into contact with your work' [1]. Studies show we spend about 90% of our time indoors [2] and the qualities of our built environment greatly impact our moods, well-being, experiences and behaviour [3,4]. Regenerative approaches [5] are those that enable social and ecological systems to maintain a healthy state and evolve. Researchers have conceptualized a regenerative sustainability approach relevant to building performance assessment, which argues that many design strategies that address human well-being (e.g., natural light, air quality, thermal comfort, natural materials) are essentially the same strategies that deliver environmental performance and climate goals [6,7] Coleman et al. (2018) argue that a critical question is where the two sets of goals overlap and reinforce each other, where they are independent, and where they might be in conflict.

For architects, there remains a need for discussion of built examples and the need to spatialize these concepts without being prescriptive. *What could a regenerative building design look like?* Translating these concepts into architectural terms, this paper presents two examples of *superarchitecture* understood here as buildings designed to be net positive and regenerative in their strategies for health promotion and environmental sustainability [7]. This term was developed in response to changes in the building industry in recent years as a result of improved understanding of not only the impacts of buildings on our environment but also on human health and well-being. The new WELL Building Standard™ rating system [8] focuses on certifying projects that demonstrate that their design, policy and operations reduce risks to and promote occupant health. The recent adoption by the Canadian Green Building Council alongside the LEED sustainable buildings rating system [9] shows there is a growing interest in the industry to begin to consider the human dimensions of green buildings. Realised examples of *superarchitecture* remain rare, and therefore, documentation and dissemination of successful projects are important.

In architecture, stereotypes and assumptions about the aesthetics of green or healthy buildings need to be discussed and debated. What do healthy buildings look like or feel like? Two recent built examples of superarchitecture are highlighted below.

SUPERARCHITECTURE: RONALD MCDONALD HOUSE BY MGA ARCHITECTS

The Ronald McDonald House of British Columbia in Vancouver, Canada by Michael Green Architects (MGA) is a residential building on a hospital campus that feels nothing like a hospital. It allows visiting families to stay while they are accessing specialised medical care [10]. The project is an extension and renovation. Growing from the old residence serving 12 families to a new 73-family facility demanded a significant shift in scale and culture to provide a new larger 'home'. In response, the architects designed the building's form and interior to be home-like by breaking up the large building mass, and making it playful and non-clinical using colour and natural materials, and reducing stress using daylight and natural ventilation.

Figure 5

Aerial view of Queensland Children's Hospital, Brisbane, Australia. Designed by Lyons, numerous green roofs connect indoor and outdoor therapy rooms, bringing in the sounds, smells, touch and views of nature into the building. Courtesy Lyons.


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3
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Lifts

Figure 6

Interior view of Queensland Children's Hospital, Brisbane, Australia. Designed by Lyons, the interior atrium space brings in light and air, with views up and through the building creating a less institutional environment. Courtesy Lyons.

In terms of well-being, MGA designed places to play, welcoming spaces for families to cook and eat together, living room spaces for socialising, and library and entertainment resources to balance the needs of privacy and community. The timber structure with exposed wood provided a residential feel inside and incorporated natural materials, which are thought to be especially important for people with compromised immune systems. From a building performance standpoint, the use of timber contributed to the building's environmental performance. The architects are known for their innovative approaches to wood construction, and the building features a tilt-up, cross laminated, lightweight timber structure and a key strategy for the facility's LEED Gold rating [10].

While not a patient-care environment per se, the Ronald McDonald House is designed intentionally to promote well-being and exceed building performance standards. In terms of performance assessment of the building, it aims for a net positive, regenerative sustainability approach. As an example of superarchitecture, the building was designed to be health promoting and exceed environmental performance standards, and it did so without sacrificing architectural design and functionality [7]. MGA successfully incorporated a residential scale, utilised a simple and natural palette of materials, and created a variety of spaces. The shared spaces are generous and comfortable, with ample daylight and natural ventilation. This project is an example of how architects can use design strategies to make emotionally supportive environments that incorporate environmentally sustainable features to offer positive co-benefits for people.

SUPERARCHITECTURE: QUEENSLAND CHILDREN'S HOSPITAL BY LYONS

The Queensland Children's Hospital (formerly named Lady Cilento Hospital) by Lyons Architects in Brisbane, (see Figure 5, 6, and 7) Australia illustrates how multi-sensory design features that incorporate colour, texture, pattern, sounds, atmospheres, and experiences can be health promoting, high performing, and architecturally inspiring. The project is another example of superarchitecture, and it challenges the architectural conventions of hospital design, offering an inviting, colourful and tactile contribution to the street level and the broader public realm. In contrast to the typical institutional appearance of health care facilities, the building is a striking urban landmark with coloured 'fins' on the exterior and oversized windows. It is designed to be non-threatening, approachable, and to lower feelings of anxiety, which is especially important as it caters to young patients who might feel uncomfortable entering the building [11].

In contrast to ordinarily inward-looking hospital designs, the building's form has large windows and balconies, allowing views into the building, and from the patient and shared areas there are views outside to the wider environment. Lyons designed the building to bring in daylight by using large roof lights and windows to create a sense of calm, to help orient visitors and to reduce the need for electric lighting, thereby improving energy performance. Double height atrium spaces have well-being and building performance benefits, including promoting natural ventilation and providing spaces for integrated artworks. Lyons chose vibrant colours for interiors based on clinical and scientific research into colour theory, whereby patients found certain colours and natural materials to be calming and to promote well-being [11]. For regular building users, the most innovative aspects are likely the series of landscaped roof terraces and gardens designed to have both environmental and health benefits.

Figure 7

Street view of Queensland Children's Hospital, Brisbane, Australia. Designed by Lyons, the hospital is an urban landmark, challenging typical conventions about the aesthetics of a medical facility by creating an inviting and colourful addition to the streetscape. Courtesy Lyons.

These spaces are biophilic design features that aim to contribute to feelings of calm and well-being and are used by patients, families and staff for recreation, therapy programs and quiet reflection. They contribute to a higher building performance as the green roofs provide thermal insulation for the lower floors of the building, reducing energy costs as well as managing storm water runoff. The inside spaces are also enhanced by these gardens, as operable windows looking onto these spaces allow patients and staff to hear birdsong and see the sky. Their locations are designed to bring the therapy outdoors, so people can sunbathe and walk on the grass. Lyons made deliberate design decisions to offer mutually beneficial relationships between people and our experiences and the natural environment. The office carried out a post-occupancy evaluation with researchers at the University of Melbourne to gain feedback and quantify how the design approaches and benefits patient well-being to inform future projects.

There are many parameters to take into consideration in a building project, and we need to make sure we spend our resources wisely. The examples above show that it is possible to realise projects that embody regenerative sustainability approaches and that are not only high performing but are also health promoting. As an industry, we need to do more than just sustain the status quo. At all scales, our environments can be designed to be multifunctional and net positive, creating a more inspiring built environment that people are motivated to maintain and renovate for years to come.

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DECLARE: AN INGREDIENT LABEL FOR HEALTHY MATERIALS

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The Declare program, developed by the International Living Future Institute (ILFI), is an ingredients label for building products. As such, it aims to promote a greener, healthier environment for construction workers, building occupants, and consumers alike. Declare was initially created as a database and resource for design teams searching for non-toxic transparently disclosed materials for their green or healthy projects. By providing a practical methodology for ingredient disclosure and toxic chemical avoidance and a simple, elegant label for designers, Declare aims to simplify the research and documentation for healthy materials.

For manufacturers, Declare is a materials transparency platform to rise above the greenwash and showcase the actual health attributes of their products through ingredient disclosure. Functioning like an ingredients label, Declare reveals the 'nutritional' information about a product so that consumers can make informed purchasing decisions (see Figure 8 and 9). A parallel exists in the food industry, which also went through a fundamental transformation with the advent of food labelling laws. At first, many companies resisted, citing trade secrets in their product's 'secret sauce'. Over time, activist consumers helped instate mandated food-labelling laws. As consumers, we now expect ingredient information; we would never accept 'secret' ingredients in the food we put in our bodies, and we should not accept them in the building products that we come into contact with every day. Declare shines a light on the use of toxic chemicals in the building industry and is also a tool for manufacturers to connect with consumers through simple disclosure.

Figure 8
Declare functions as an 'ingredient label' for building products, providing transparency in the sourcing, toxicity and contents of building products. (Courtesy: International Living Future Institute)

Figure 9
In addition to 'ingredient information', Declare includes information regarding raw material extraction, end-of-life scenarios, red-listed material usage, VOC emissions, and life expectancy. (Courtesy: International Living Future Institute)

DECLARE WITHIN THE FRAME OF THE LIVING BUILDING CHALLENGE

Declare is a resource for Living Building Challenge (LBC) and other building project teams to identify healthier materials. LBC is a holistic performance-based green building certification program. It uses the metaphor of a flower because buildings should function as cleanly and efficiently as a flower, getting their energy from the sun and operating within the water balance of their place.

Declare.

Your Product
Your Company

Final Assembly: City, State, Country
Life Expectancy: 000 Years
End of Life Options: Recyclable (42%), Landfill

Ingredients:

Your First Ingredient (Locally Sourced Location, ST), **Sustainably Sourced Ingredient** (Location, ST), **Non-toxic Item** (Location, ST), **Living Building Challenge Red List***, **Another Componant**, **US EPA Chemical of Concern**, **Last Ingredient**

Living Building Challenge Criteria:

XXX-0000 EXP. 11/11/2011
VOC Content: 0.00 mg/m³ VOC Emissions: CDPH Compliant
Declaration Status
☐ LBC Red List Free
☒ LBC Compliant
☐ Declared

MANUFACTURER RESPONSIBLE FOR LABEL ACCURACY
INTERNATIONAL **LIVING FUTURE** INSTITUTE℠ declareproducts.com

End-of-life options: take-back programs, salvageable or reusable in its entirety, recyclable (%); landfill; hazardous waste.

Ingredient are reported by component. Ingredients without restriction appear in grey; **Red List chemicals appear in dark orange; EPA COC and REACH chemicals appear in light orange.** (Reported raw material extraction locations are listed in parenthesis.)

Declare Identifier for company and product, valid for 12 months.

VOC Information and CDPH Compliance.

Verification that product complies with Living Building Challenge Red List.

The LBC [1] comprises seven performance areas, or ‘petals’: Place, Water, Energy, Health & Happiness, Materials, Equity and Beauty. It thus provides a clear framework for design teams looking to create regenerative buildings, and a rigorous third-party verification process to ensure those aspirational goals are met.

LBC has strict standards for healthier interior environments, healthy materials and Biophilic Design. When it was first launched in 2006, professionals believed that meeting the Energy or Water petal would be the challenging aspect of the program. However, the Materials Petal became the most challenging component because it required a wholesale transformation of the building product industry.

MATERIAL RED LIST

Particularly difficult was the Red List [2], one of the requirements of the Materials Petal. The Red List is comprised of 22 of the worst-in-class materials and chemicals that are ubiquitous in the built environment. These are carcinogens, persistent organic pollutants, and reproductive toxicants, many of which are bio-accumulative, meaning that they build up in organisms and the broader environment, often reaching alarmingly high and dangerous concentrations as they travel up the food chain. An example of one class of these chemicals is perfluorinated compounds, often found in stain treatments and coatings. These chemicals are a known carcinogen and reproductive toxicant, and do not break down naturally in the environment; they are now so pervasive they are in the bloodstream of nearly every person. The purpose of the Red List is to identify what is in building products and to push manufacturers to avoid the use of these toxic chemicals entirely from the whole life cycle of a product—from its manufacture to exposure risk in use, to end-of-life.

Few teams understood the magnitude of the challenge in front of them at the start. The Red List was useful in helping to identify what chemicals to avoid, but architects were unsure how to ask the right questions of manufacturers, and manufacturers were unwilling, unsure, and at times simply unable to respond. To address this disconnection, the International Living Future Institute developed the Declare program to require manufacturers to be transparent about their ingredients.

RESPONSIBLE AND TRANSPARENT MANUFACTURING

Declare allows manufacturers to disclose the ingredients within their products to all LBC teams. Through the Declare database, product ingredients are screened and vetted against the LBC Red List. When project teams select a Declare product, they only submit the unique identification number in the certification submittal; there is no additional vetting or documentation necessary.

At first, many manufacturers were hesitant to disclose their ingredient information, citing proprietary trade concerns as well as concerns of reaction from consumers about disclosure of potentially harmful ingredients. However, over time, manufacturers have found that pursuing Declare and transparency can be good for business. There is a growing movement for toxic chemical evaluation and disclosure that has swept the industry since the introduction of Declare and other transparency programs in 2012. Companies are finding that transparency is key to successful long-term sustainable business and product development strategies.

To participate in Declare, a manufacturer has to put together a comprehensive list of all the ingredients in a product to ensure there are no chemicals on the Red List. Just putting together this ingredient list is instructive: a detailed inventory of chemical contents facilitates a much deeper understanding of a product's chemistry, production process and supply chain. Often, manufacturers who engage in the process realise that they are already capable of developing healthier, safer products by using readily available alternatives. Transparency within a company or supply chain is the first step towards healthier products, though challenges remain due to lack of chemical information and persistent and often unnecessary proprietary ingredient claims.

Moving a company from a culture of secrecy to one of openness, collaboration, and stakeholder engagement requires hard work. Retooling a production line, or introducing a new formulation to eliminate toxic chemicals, can be expensive and time-consuming, but that investment has enormous benefits: competitors will necessarily have to go through the same process to catch up when regulations and consumer awareness advances. Companies who conduct the hard work now position themselves months or even years ahead of their competition. Since its launch in 2012, Declare has over 2,000 products from 175 manufacturers representing tens of thousands of individual products.

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TEMPERATURE VARIATIONS FOR HEALTH

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Thermal comfort research from the 1960s and 1970s, e.g. [1], has resulted in the notion that a uniform and constant temperature in which occupants feel on average thermally neutral will yield maximum occupant thermal comfort. However, strict conditioning of the indoor climate leads to excessive energy consumption [2], and hence, contradicts sustainability goals aiming to lower environmental impact. Although the adaptive comfort model has gained more attention over the last few years, the application is highly limited and restricted to buildings without HVAC systems [3,4], although the concept has been demonstrated to also be viable for other buildings [5].

Moreover, although the adaptive comfort model allows for seasonal variation, diurnal changes are still very limited. Interestingly, recent research has shown that a uniform climate may lead to an ‘untrained’ human thermoregulatory system, but that exposure to temperature variation may induce beneficial health effects [6]. Exposure to cold can increase human heat production and thus increase energy expenditure, which has been shown to positively affect type 2 diabetes [7]. Recent evidence has also shown that heat might improve glucose metabolism and can improve cardiovascular health [8]. Therefore, exposure to temperatures outside the thermoneutral zone can bring significant health effects. This does not necessarily mean that building occupants should suffer from thermal discomfort as mild variations have also been shown to be effective.

Moreover, several studies have shown that people exposed to varying indoor temperatures have a larger range of thermal acceptability, e.g. [9]. Besides positive health effects, temperature variations can be used to induce alliesthesia, i.e. ‘thermal pleasure’ [10,11]. This section thus elaborates on the paradigm shift from static to dynamic indoor environments and how this shift affects our physiological health and thermal comfort. Also, a brief insight is provided into state-of-the-art laboratory facilities and measurement tools for field studies.

MEASUREMENT IN RESPIRATION CHAMBERS AND SURVEYS

The Metabolic Research Unit Maastricht (MRUM) is a facility built to study human metabolism under controlled environmental conditions. Metabolism refers to those chemical reactions that convert food into energy, build proteins and other building blocks, and are responsible for waste processes. Heat production is an important result of the metabolic processes. The so-called ‘respiration chambers’ at MRUM are air-tight and allow full control of air temperature, air humidity, air speed and air pressure. The key strength of the respiration chambers is the high-end measurements of oxygen and carbon dioxide concentrations, which allow for the calculation of the occupants’ metabolic energy expenditure and facilitate the study of cognitive performance under various gas concentrations. Other physiological parameters that are routinely measured include skin temperature, core temperature, sweating, shivering, physical activity, heart rate, blood pressure, blood perfusion and several blood plasma metabolites (e.g. adrenaline, cortisol, melatonin, endorphins and dopamine, glucose, insulin). Some of the measurement devices used to measure these physiological parameters are shown in Figure 10.

Figure 10

Measurement equipment for physiological measurements: (a) iButtons for skin temperature, (b) blood pressure monitor, (c) Equivital heart rate monitor and data collection from core temperature pill, (d) Equivital core temperature pill, (e) MOX activity monitor, (f) Polar belt heart rate monitor, (g) fitbit activity and heart rate monitor (used in field studies).

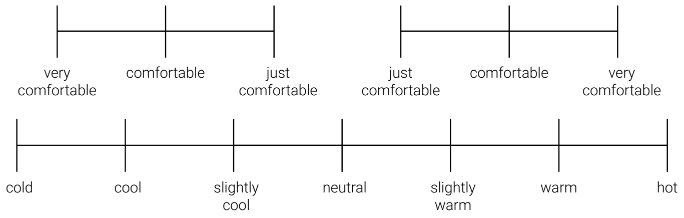


Figure 11

Visual Analogue Scales used in the questionnaires to assess thermal sensation (above) and thermal comfort (bottom). Note that the thermal comfort scale is divided into two parts to urge participants to indicate whether they perceived the thermal environment as ‘comfortable’ or ‘uncomfortable’.

Self-perceived effects are assessed using questionnaires, including thermal sensation, thermal preference, thermal comfort, and thermal acceptance. Thermal sensation and preference are reported via visual analogue scales (VAS) using the standard 7-point ASHRAE scale [12] and another symmetrical VAS scale to indicate thermal comfort [13], see Figure 11. Note that the thermal-comfort-scale is divided into two parts to urge participants to indicate whether they perceived the thermal environment as ‘comfortable’ or ‘uncomfortable’.

Measuring the parameters mentioned above can tell us more about the metabolic health effects of various indoor climate scenarios and what is perceived as comfortable, which helps us to design optimal working environments.

STATIC VS DYNAMIC INDOOR TEMPERATURE: HUMANS’ ENERGY METABOLISM, AND PHYSIOLOGY

Metabolic diseases such as obesity, cardiovascular diseases and type 2 diabetes are global challenges and significant medical and financial burdens [14,15]. Therapies for these conditions are often, amongst other pharmacological treatments, aimed at calorie restriction, for example, as a combination of diet change and exercise. Unfortunately, long-term motivation to adhere to training programs and dietary regimes is generally poor.

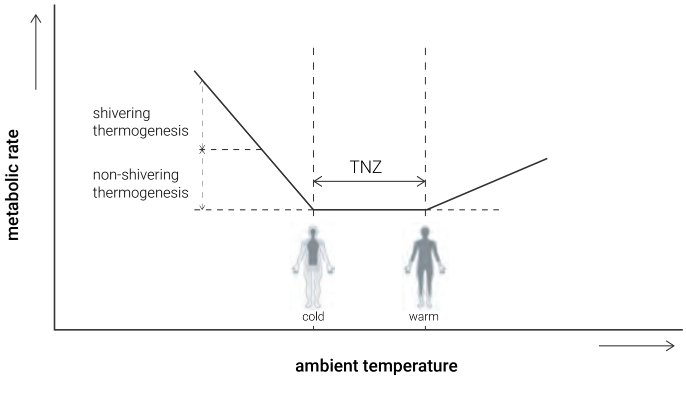
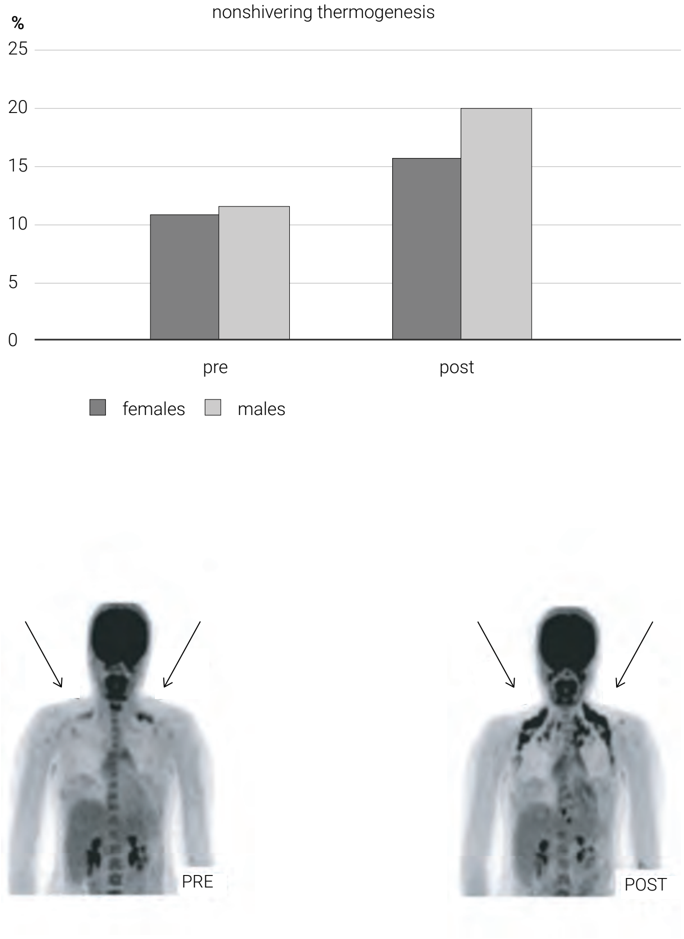


Figure 12
The physiological thermo-neutral zone (TNZ, adapted from [18]) (non-shivering thermogenesis, NST; shivering thermogenesis).

Figure 13
Cold acclimation increases non-shivering thermogenesis and brown fat activity (arrows) before (PRE) and after (POST) cold acclimation [19].



Importantly, it has been indicated that certain environmental parameters, especially temperature, might play an important role in metabolic health. A static, uniform thermal environment has been suggested to play a role in the global 'obesity and diabetes epidemic' [6,16,17]. However, on the contrary, exposure to certain thermal conditions has been shown to bring about beneficial health effects: the cold can increase human heat production and thus increase energy expenditure, which has been shown to affect type 2 diabetes positively [7]. Recent evidence at Maastricht University indicates that heat might improve glucose metabolism and can improve cardiovascular health (data not yet published; in prep). In summary, exposure to thermal conditions outside the so-called thermoneutral zone has been shown to induce beneficial health effects [6] (see Figure 12).

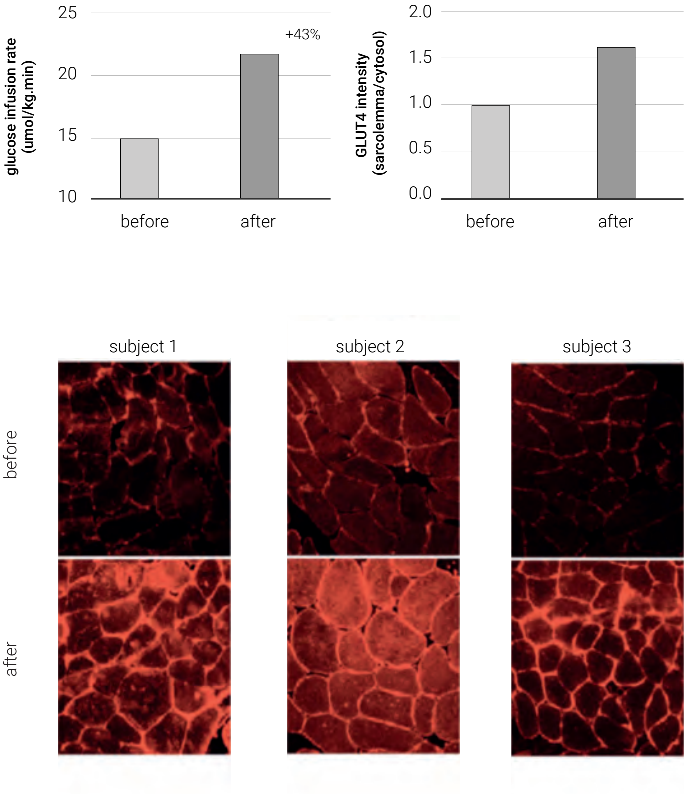


Figure 14
Cold acclimation increases insulin sensitivity and skeletal muscle glucose transporter type 4 (GLUT4) intensity [7].

Dynamic indoor conditions may provide a viable alternative to a tightly controlled uniform thermal environment and help to improve health while simultaneously ensuring thermally acceptable/comfortable conditions for building occupants. Note that in their natural habitat, humans used to be exposed to varying ambient conditions such as temperature, humidity and airspeed. Past research has addressed the individual impact of several environmental conditions, but more recently, the effects of dynamic indoor temperature variation have been studied. For example, Schellen et al. [9] studied the effects of drifting temperatures on thermal comfort, productivity and health in young adults and the elderly. A recent review highlights the positive health effects of dynamic temperature variations outside the thermal comfort zone [6]: mild cold and warm conditions induce important changes in metabolism and insulin sensitivity (Figure 13 and 14), which in turn positively affect the metabolic syndrome (obesity, cardiovascular diseases and diabetes), as well as reduce the risks of cardiovascular diseases.

STATIC VS DYNAMIC INDOOR TEMPERATURE: THERMAL SENSATION DOES NOT EQUAL THERMAL COMFORT

A widely used tool is the predicted mean vote (PMV) model of Fanger [1]. This model is included in current building standards to predict thermal sensation. Hence, strictly speaking, it cannot be used to predict thermal comfort, but only thermal sensation. It assumes that a person is most comfortable in a thermally neutral condition, which is not necessarily true, particularly not in dynamic conditions. Many researchers have shown the limitations of the model, e.g. [20,21]. According to de Dear [11], the PMV theory from Fanger has led to the thermal comfort mantra 'cool, dry, still indoor air', which has been realised through static isothermal indoor climates.

There are strong indications that thermal sensation does not equal thermal comfort and that the relationship between comfort and sensation may be different in dynamic conditions and static conditions. In the project DYNKA [22,23], which aims to disentangle these questions and develop design principles for dynamic office environments, experiments are conducted comparing static versus dynamic indoor temperature scenarios.

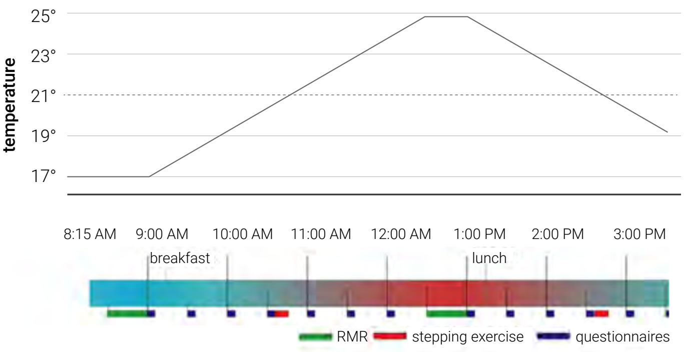


Figure 15

Temperature and measurement schedule. The red line indicates the constant temperature protocol (17°C) and the black line represents the drifting temperature protocol (17-25°C). Measurements start at 8:15 AM and end at approximately 5:00 PM and are similar in both protocols. Resting metabolic rate (RMR) is measured at 8:30 AM, 12:30 PM and at 4:30 PM for 30 minutes.

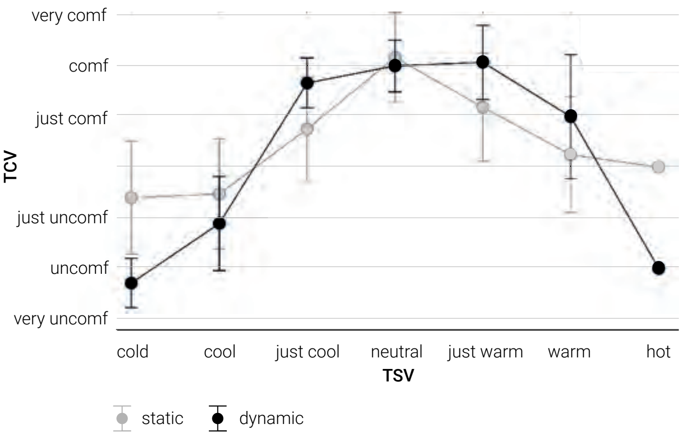


Figure 16

Thermal Comfort Vote (TCV) vs Thermal Sensation Vote (TSV) for the static indoor temperature (21˚C) and the dynamic indoor temperature scenario (19˚C at 9:00 h, to 24˚C at 12:00 h, and back to 19˚C at 17:00 h).

Participants undergo two full days of testing in the MRUM climate chambers, in which a typical office environment is emulated. In one condition, the ambient temperature is kept constant at 21˚C, and in the transient condition (tests during winter season) the temperature is varied between 17˚C in the morning and reaches 25˚C around lunch after which it drops back to 17˚C. The relative humidity is maintained at 50% RH, and airspeed is maintained at approximately 0.15 m/s. An overview of the experiment is provided in Figure 15.

Linked to DYNKA, the PERDYNKA [24] adds Personal Control Systems (PCS) [25] to the dynamic ambient temperature profile to mitigate individual differences in thermal comfort perception. PCS can overcome the shortcoming of 'one climate fits all' and helps extend the thermal comfort range allowing for more dynamic ambient conditions. The combination of PCS and moderate temperature drift has the following potential benefits: (i) comfort control on an individual level, (ii) positive health effects, and (iii) increased energy efficiency.

Figure 16 shows the different relation between thermal comfort and thermal sensation for dynamic thermal conditions compared to static thermal conditions. The results are based on a two-week experiment in a living lab office setting conducted in October 2018, including 10 test subjects. During one week, the indoor temperature was maintained at 21˚C, and in the second week the indoor temperature was varied, analogous to the temperature scenario in Figure 15: from 19˚C at 9:00 h to 24˚C at 12:00 h, and back to 19˚C at 17:00 h. Interestingly, although the temperature was maintained around 21˚C, participants' thermal sensations span from cool to warm (with incidental occurrences of cold and hot).

Moreover, the office occupants felt more comfortable in the thermal sensation range 'just cool' to 'warm' in the dynamic scenario compared to the static scenario, although comfort sharply decreased towards the extremities of thermal sensation. Note that the temperature profile was rather extreme as natural temperature variations in buildings are usually milder. Hence, the results strongly indicate that climate designers, architects and engineers should be rethinking the current paradigm on thermal comfort to allow more variation, and hence, facilitate energy reduction (as the course of the indoor temperature is closer to the natural diurnal temperature cycle), and at the same time provide healthier environments.

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BIOMEDICAL SENSORS AS INVISIBLE DOCTORS

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Estimates provided by the National Fire Protection Association (NFPA) indicate that between 2012 and 2016 U.S. fire departments responded to a yearly average of 355.400 home structure fires [2]. Comparatively, the number of Americans per year that suffered a heart attack is nearly double [4]. Taking into account that heart attacks are just one of a wide range of severe health disorders, there is an opportunity to devise vigilant household devices that do for health monitoring what fire detectors have done for home structure fire prevention.

Biomedical sensing, analysis, and interpretation are basic elements of well-being assessment, preventive healthcare, and the creation of better healing environments. While wearables have contributed to making such elements a more pervasive and integral part of people's daily lives, regenerative design can take health monitoring one step further.

By incorporating biomedical sensing in the habitable space at an architectural level, future buildings can potentially have multiple components continuously monitoring their occupants. Although these are not likely to 'replace' regular doctors, they may act as an invisible proxy or complement to regular care. This paper provides a brief introduction to biomedical signals and sensing, describes some of the ways in which they can be incorporated in regenerative design, and presents practical examples of tools and conceptual installations that illustrate how the architectural space of the future may become an 'invisible doctor'.

As set forth by the Organisation for Economic Co-operation and Development (OECD), Eurostat and World Health Organization (WHO) [1], an integrated healthcare service includes promotive, protective, preventive, curative, rehabilitative, and palliative care. Each component serves specific needs of individuals, families, or populations throughout their lives and, considering that people spend 85-90% of their time indoors [3], it is only logical to consider architecture as a component of a holistic healthcare approach.

Regenerative design can be considered as a process-oriented approach to creating resilient and equitable systems that satisfy fundamental human needs. As such, it can benefit from new emerging technologies to devise spaces that allow the integration of biomedical sensing in the architectural space with the threefold objective of 1) assessing comfort and general health; 2) facilitating preventive healthcare (i.e. detecting potential health issues and act at an early stage); and/or 3) creating hospitable health environments (i.e. provide better support to subjects suffering or recovering from health issues). In its essence, the interior environment can virtually become an invisible assistant to medical practitioners, monitoring the status of its occupants and potentially enhancing the individual components of integrated healthcare services.

There are multiple challenges to bring such a vision to life, but considerable opportunities as well. The following sections describe different concepts associated with biomedical sensing, review some of the tools currently available, present illustrative case studies, and discuss possible paths to move forward.

A PRIMER ON BIOSIGNALS

The human body is driven by several physiological phenomena, which generally have physical (e.g. DNA), chemical (e.g. neurotransmitters), electrical (e.g. cellular action potentials), and mechanical manifestations (e.g. respiratory cycles). Regardless of their nature, the term *'biosignal'* has been commonly accepted to summarise the description of all physiological phenomena in the broader sense [5]. Many of them can be captured using specialised equipment (see for example Figure 17) and represented as computationally manageable inputs. This enables the creation of systems that incorporate software and hardware components capable of sensing and responding to biosignals [5][6], also known as physiological computing systems [7].

For many decades, biosignal acquisition has been performed exclusively at medical facilities (or the equivalent), often requiring cumbersome equipment and procedures. This is still the norm in many cases (e.g. medical imaging), and usability constraints often hinder a more widespread deployment of biomedical sensing [6]. However, nowadays, it is already possible to track a plethora of biosignals with pervasive personal digital technologies, such as smartphones and/or wearable devices [8]. Examples from the (albeit still limited) literature range from mobile apps that record behavioural information of the user to support early detection of Parkinson disease [9], to smart watches capable of detecting atrial fibrillation from a single lead Electrocardiogram (ECG) [10].

Figure 17
Example of a typical sensor application for psychophysiological data acquisition setup, in this case, shown in a virtual reality environment.

Due to the underlying measurement principles, some biosignals can be detected with the sensors integrated into everyday objects or in the space surrounding the user, rather than requiring direct placement on the body. Recently coined as 'off-the-person' [11], this approach does not rely on accessories that users need to remember to wear, that require charging, and/or require users to change their daily routines. Abandonment rates above 30% are still common for wearable technologies [12].

SYSTEMATIC BIOMEDICAL SENSING

Although wearables have taken us one step further in the evolutionary path of biomedical sensing, the latest developments are paving the way for more profound changes through off-the-person health assessment in a pervasive way. In speciality applications, such technologies are already deployed for mass screening.

For example, Infrared Thermal Image Scanners (ITIS) are often used in airports to screen travellers for influenza [13]. Another example is based on video sequences captured using standard cameras, [14] researchers developed a method capable of enhancing chromatic differences between individual frames, enabling the estimation of Instant Heart Rate (IHR). The approach, designated as Eulerian Video Magnification (EMV), is even reportedly capable of performing simultaneous IHR estimation when multiple subjects appear in the video frames (e.g. enabling basic health assessment for all the occupants of a room at the same time). Another example uses radio frequency interferometry. The Vital-Radio introduces a wireless sensing system capable of contactless measurement of breathing, IHR and motion data within an indoor space [15]. This technique does not require the subject to wear any special accessory nor perform a particular action, and it can also work when the subject is not in line of sight of the system (i.e., it can 'see through walls').

Even for more minute signals such as the ECG, seamlessly integrated sensing approaches are appearing. The 'Aachen SmartChair' [16] is capable of measuring quality ECG-like signals with sensors integrated in an off-the-shelf office chair, even when the subject is wearing clothes. Improving upon contact-based sensing, researchers have proposed [11][17] a method of acquiring clinical-grade ECG data, consisting of sensors that can be integrated into regular household items such as a computer keyboard, the armrests of a chair, or any other surfaces with which the occupants interact using both limbs. A variant of this method has been recently applied to a smart toilet seat that measures the ECG and other parameters [18].

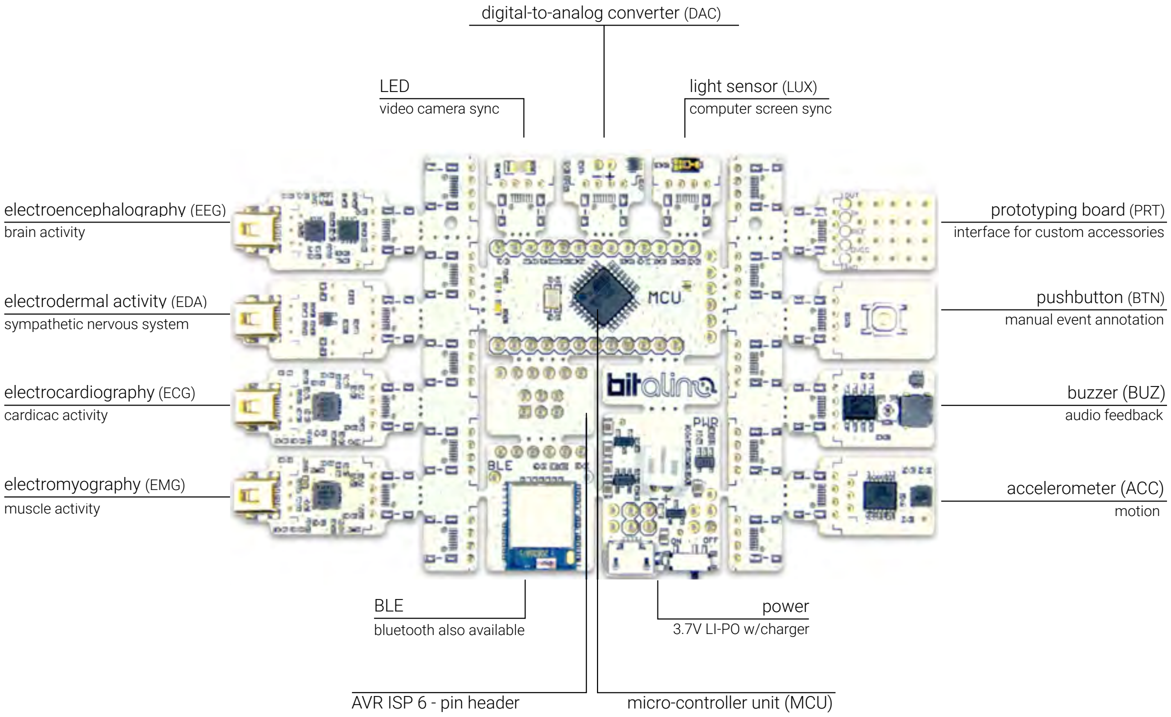
FROM THE LAB TO THE ARCHITECTURAL SPACE

Up until recently, prototyping tools to experiment with and effectively integrate biomedical sensing in architectural design required specialised knowledge and provided limited flexibility. However, nowadays, there are numerous Software Development Kits (SDK) and hardware platforms, enabling virtually anyone to experiment with biomedical sensing supported by open source and low-cost tools.

One such platform has been introduced in [19], showing comparable performance to that of gold standard devices for multiple biosignals [11][20][21]. The hardware (Figure 18) includes all the components needed for sensing and wireless transmission of multiple biosignals, complemented by software tools ranging from low-level SDKs to signal analysis and interpretation packages. Several examples of the synergies between this platform and architectural design already exist.

Figure 19

Sensors integrated into the steering wheel of a vehicle for measurement of ECG, linear and angular acceleration, to allow early stage detection of fatigue and cardiovascular problems.



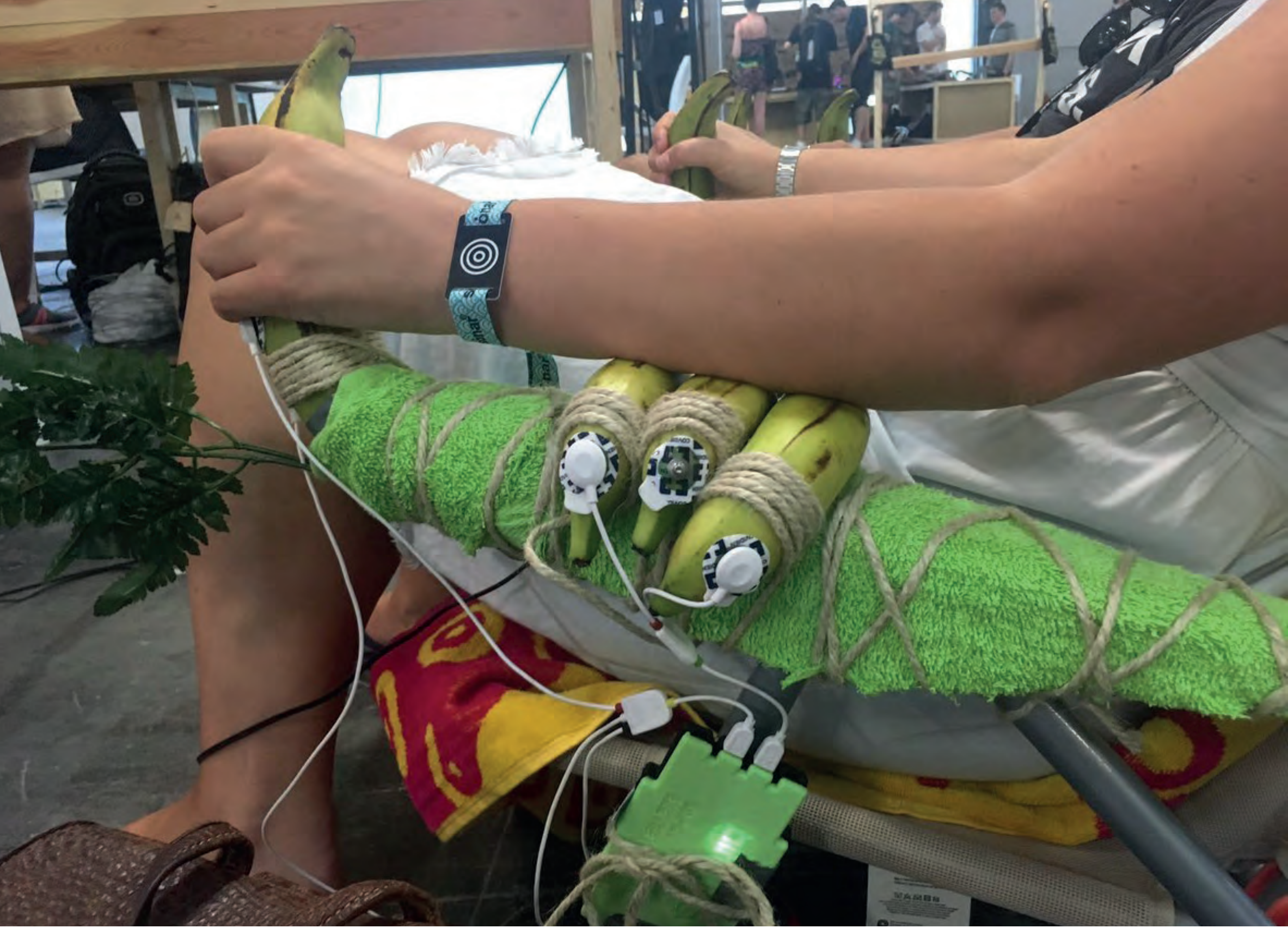
Working at the interface between wearables and architectural elements, the 'Atmospheric Delight' installation [22] produces generative feedback loops between spatial scenarios and user experiences. In this work, a building is considered as a repository of indoor microclimates and use biosignals to assess the comfort level of the user and dynamically control the thermal system of the room accordingly.

A system named 'Pulse Music' has the goal of transforming the patient experience and contributing to the conversion of the environment of a hospital into a more hospitable environment [23]. It uses biosignals to automatically adapt the tempo of a piece of music in response to a listener's IHR. As reported, this system represents a novel approach to health interventions, where new technology can create real-time feedback loops between a patient and his/her surrounding space.

Figure 19 depicts a system conceived for preventive health. The steering wheel integrates a biosignal acquisition device that measures the ECG and linear and angular acceleration, intending to allow early stage detection of fatigue and cardiovascular problems. An interesting aspect of this work is the fact that conductive leather is used as the interface between the sensor and the body, preserving the look and feel of the original part.

Figure 18

Example of the biomedical development toolkit BITalino in its (r)evolution Board Kit Bluetooth Low Energy (BLE) configuration. Printed circuit board for the BITalino hardware, annotated with all the base sensors and different supporting components.



This technology could be transposed to architectural space, for example as the armrest of a chair wrapped with this material, to measure the ECG whenever a subject is sitting. Incorporating biomedical sensing in the architectural space with which the occupants interact and benefit from is a natural leap forward in architectural design.

By collecting biosignals in a nearly invisible manner, the space can adjust to perceived changes in the comfort and/or health status of its inhabitants as assessed by the sensors [22], detect potential health problems at an early stage and act preventively before they escalate, and/or contribute to improve the presence in a hospitable space once more serious issues occur [23] [24]. Significant advances in instrumentation, materials, and computational methods have made available a plethora of tools that begin to open up new possibilities for collaboration between designers, health professionals, and engineers in unprecedented ways, without the previous constraints for which they were known until recently.

Figure 20

Advances in instrumentation, materials, and computational methods are enabling novel and creative uses of physiological sensing; in a recent display, even fruit has been used as the interface with the user. Beach chair for Electrocardiography (ECG) and Electrodermal Activity (EDA) measurement using bananas as the interface with the subject's body (Credits: Turo Pekari).

This possible collaboration can lead to innovative applications, for example, even using fruit as the user-interface (see Figure 20). There are still several challenges to overcome. Occupant identification, data privacy protection and preservation, or potential acceptance by some user groups (for example those stressed by constant monitoring), are some challenges related to users. Large-scale deployment and maintenance of biomedical sensing equipment, or finding useful information amongst the data deluge generated by always-on/always-connected devices, are some examples of technical and analytical challenges. However, the holistic and interactive feedback goals of regenerative design can support this growing paradigm shift and represent an interesting collaboration between science and engineering to drive innovation.

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ARCHITECTURAL DEVICES TO REDUCE AIR POLLUTION IN CHINA

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The master program of 'Architecture and Extreme Environments' programme aims to respond to global environmental and social challenges. Through site-specific 1:1 prototypes named 'architectural devices', which have been positioned in remote world locations, new technologies and new designs are tested through the lens of regenerative design [1]. During the winter of 2016, the program of the Royal Danish Academy settled in the Gobi Desert to develop solutions to mitigate the region's climate, ecology, resource and wellbeing issues. Among the several issues approached, this section focused on how to respond to local air pollution, which is heavily compromising people's health in the cities of Lanzhou, Lanzhou New Area (a newly built satellite city of Lanzhou known as LNA), Jilantai and Donhuang.

THE ARCHITECTURE OF EXTREME ENVIRONMENTS

In close collaboration with local communities, scientists and manufacturers, the programme of Architecture of Extreme Environments, designed by David Garcia, pursues regenerative design solutions that re-establish a positive link between natural resources and the built environment. Its focus includes remote areas, highly dense cities being affected by frequent flooding, extreme dryness or humidity, extreme cold or hot seasons, high pollution and loss of biodiversity in territories in which human activities have severely damaged the ecosystem. Substantially, the programme studies in depth human activities that lead to the exhaustion and the damaging of the natural capital of a site.

In these expeditions - run in northern regions, desertified areas and tropical forests across the world - the main aim is to design innovative settlements, buildings and technologies that re-establish a positive link with the land,, flora an fauna, water, energy, materials, air, and human lives and activities [1]. Whereas in architectural education the typical scope is to form architects that can reduce environmental impacts in the built environment, this program aims at re-enabling the capacity of the local and the broad ecosystem to function.

The course thus seeks to investigate site-specific knowledge and local design traditions that have allowed for sustainable, resilient and healthy environments for centuries. Another focus is the scientific study of local flora, fauna and other forms of nature as a trustworthy source of inspiration. Finally, there is a deep integration of science and technology in design to create a more extensive architecture's spatial vocabulary. Core to such activity is the development of experimental prototypes, named 'architectural devices' that incorporate such values and that possess architectural quality.

GOBI DESERT AND SURROUNDING CITIES

In China, air pollution is a real emergency. In 2010 alone, 1.2 million people died from health issues caused by ambient particulate matter [2]. In 2011 The World Health Organisation named Lanzhou, the capital of the Gansu Province, China's most air polluted city [3]. In the Gobi Desert region (Figure 21), the high levels of air pollution are primarily due to fine sand particles carried by the wind and less a result of human-made pollution such as traffic or burning coal.

This is in part due to Lanzhou's geography, situated between two mountain ranges next to the Gobi Desert, which results in large quantities of dust being blown into the city, while the air remains trapped in the valley. This issue is no longer confined to China's North Western region as the Gobi's sands are spreading across the country through the process of desertification, which is becoming one of the most significant environmental catastrophes facing China, and which costs over 89 billion RMB per year, around 1% of China's GDP. Other factors influencing air quality are the heavy industrial processes thatare still dependent on coal, and the heavy traffic in urban areas [4].

Figure 21

A mix of pollution and sand coming from the desert compromises Air in inhabited centres. (photo: A. Kongshaug)

		air quality index (aqi)
0-35	good	air quality is considered satisfactory, and air pollution poses little or no risk
35-75	moderate	air quality is acceptable; howaever, for some pollutants there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution
75-115	unhealthy	members of sensitive groups may experience health effect, the general public is not likely to be affected
115-150	very unhealthy	everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects
150-250	extremely unhealthy	health warnings of emergency conditions, the entire population is more likely to be affected

Table 1
Air quality Index. Table of reference values.

Recording in the area of Lanzhou of the Air Quality Index (AQI) performed during the expedition shows that air quality is very or extremely unhealthy. The purpose of the AQI is to help the understanding of what local air quality means to health. To make it easier to understand, the AQI is distributed into six levels of health concern. For example, an AQI value of 50 represents good air quality with little or no potential to affect public health, while an AQI value over 300 represents air quality so hazardous that everyone may experience severe effects (Table 1).

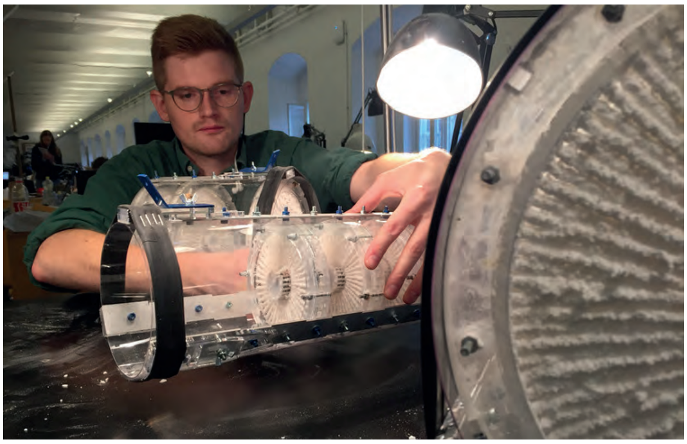
THE CONCEPT OF ARCHITECTURAL DEVICE

The proposed work explores the idea that designers can acquire augmented environmental information with the use of customised 'architectural devices' (6). Via the devices (Figure 22), students engage in hyper-specific data collection, revealing ways in which the design of the built environment may have a regenerative effect on the environmental issue. By responding to specific conditions, the devices prove solutions that can restore, renew or regenerate a site capitalising on occurring climatic cycles (e.g. atmospheric, ground and water), rationalising the courses of local sources (energy and materials) and creating a sustainable environment that creates both human and ecosystem health.

Devices are built and used to measure, understand and modify local fluctuations of temperature, breezes, humidity, rainfall, sky condition, light quality, energy potential and pollution. Such interplay reveals opportunities for future fine-tuned regenerative tactics for the built environment.

Figure 22

Example of preliminary experiments in phase one of the device process. The students work in Copenhagen with air salt filters (photo by David Garcia)



The architectural devices are portable. Once they are installed on a site, they measure specific patterns occurring in nature or built environments by collecting climatic, physical and chemical data, or by recording social behaviours. The devices respond to these data and information by reacting to them, for instance by moving, by changing colour, by projecting image or by sending signals of different kinds. Data are thus collected for future scientific and architectural uses. However, data also become the input for real-time artistic performances aimed at creating an awareness of environmental and health dangers and solutions to issues.

The devices functions passively, and furthermore have regenerative functions. For instance, they can use waste polluted materials and upcycle them, or they can purify water, air and soil. The architectural devices are thus performative prototypes that anticipate and test future architectural regenerative solutions and engage with the local community.

DEVICES ENGAGING WITH AIR POLLUTION

Four of the twenty devices designed in the 2016 mission to Gobi Desert aimed at reducing air pollution, or, in a circular sense, to transform pollution into a resource. The devices were conceived to improve air quality, health and well-being of city inhabitants. Devices were placed in Jilantai, Donhuang, Lanzhou and LNA. It was possible to record high levels of particle pollution blown into the city from the deserts and other human-made sources of pollution including hazardous gas pollution resulting from construction, industry, coal burning and traffic. The devices were equipped with laser particle detectors to gather information such as AQI, pm1.0, pm 2.5, pm10 and hazardous gas content. Air temperature, humidity, speed and direction were also measured.

The first architectural device described here was deployed in both Jilantai and Donhuang in the Gobi Desert and aimed at designing a shelter for sleeping in air-polluted areas. Airborne particulate matter was filtered by using salt crystals to extract pollution driven by moisture through a series of cylindrical salt crystal (a locally available material) filters integrated into a tent structure (Figure 23 - 25). An ancient Mongolian building technique inspired the tent design. Results showed a significant indoor reduction of particle pollution when compared to the outside (Table 2). The work shows the high potential of locally sourced material filters, and it can be scaled to various residential units.

Figure 24

Tent structure designed to filter polluted air using salt crystals. By evaporating the mix of salt and water taken in the regions around the Gobi desert, the strings on the filters grow the air cleaning crystals. An acrylic frame hosts the system and facilitates the air exchanges in the tent. (Design and image by Aleksander Guldager Kongshaug, Photograph by David Garcia)

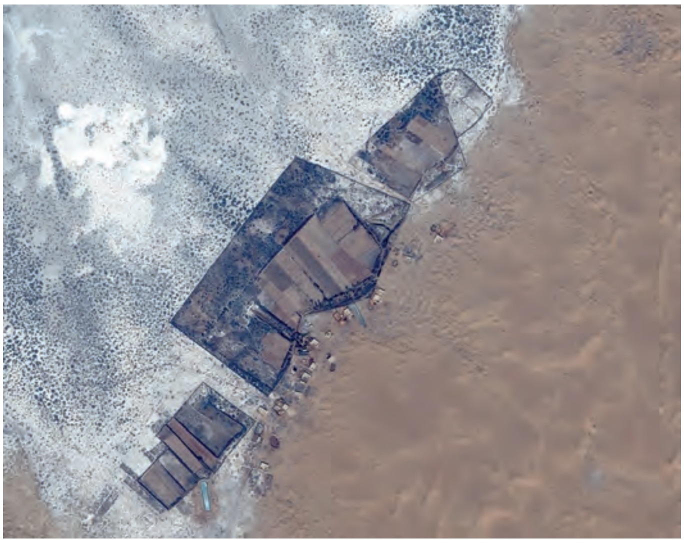


Figure 25

The tent structure designed to filter polluted air using salt crystals. It can be handled by a single person who controls the three 'tent wings' and the chimney in the middle of the tent (Photograph by David Garcia)

Figure 23

Overview of one of the several Salt Lakes in the Gobi Desert. The abundant salt is used in the air cleaning filters. (Image provided by Aleksander Guldager Kongshaug)

test	aqi	pm10 µg/m³	pm2.5 µg/m³	pm1.0 µg/m³
outside	122	65	52	41
inside	29	13	10	6

Table 2

Data registered from outside and inside the tent

Figure 26

Kite designed to mechanically separate airborne dust without the use of filters. (Design and photo by Anders Cochet Svinkløv)

Mechanical and industrial processes of air filtration and the Chinese cultural tradition of kite flying (Figure 26) inspired the second architectural device. It consisted of two kites that use shape to manipulate airflow in such a way that airborne dust is separated and contained. The intake of the kite forces air into a spiralling flow that creates centrifugal forces driving the dust particles into the inner barriers of the device. The airflow streams to the cyclone-separators at the bottom of the equipment and directs air into dust-containers (Fig.8). A series of tests were carried out in Lanzhou and LNA in varying wind and air pollution conditions. The results showed a recurring pattern. When wind speeds are above 2m/s the number of dust particles is lower. This suggests that controlling air flows and velocity by urban form can be used to polarise pollution in certain areas, thereby allowing it to be absorbed.

The third device is an air cleaning technology, which is based on electrostatic attraction through a wind-powered triboelectric air purifier. The design uses the static precipitator principle, which is often used for collecting exhaust smoke particles in industrial smokestacks. When the device is in operation, a woollen brush (+) rotates against a plastic container (-), in which the particles are collected. The brush is part of a vertical windmill along with a 12v generator that feeds electricity to run the suction fan. The fan guides polluted air from an intake vent through the filter unit (Figure 27). The device was tested in Lanzhou and LNA, in different wind and air pollution conditions. Tests showed that there was a reduction in PM2.5 and the AQI (Table 3), so the system was studied further and developed into facade components.

measurements every 8 minutes	wind speed (m/s)	pm2.5 (µg/m³)		aqi	
		pm2.5 intlet	pm2.5 outlet	aqi intlet	aqi outlet
1	2,1	57	49	133	118
2	2,2	53	46,5	126	114
3	1,9	42	48	114,5	101,5
4	2,1	53	49	126	117,8
5	3,2	25,3	21,9	70	64
6	3,0	53,2	46,8	126	113,9
7	2,5	49	42,3	118	103,5
8	2,6	54,8	47,8	130,7	114,3

Table 3

The difference in the inlet and output measurements. The green colour represents the cleaning effect magnitude.

Figure 27 (Next page)

Wind-powered Triboelectric Air Purifier. The Triboelectric Air Purifying Unit capitalises on the static properties inherent in different materials, creating a static charge, which attracts and collects unhealthy particles from the air. (Design of Esben Wisbech Sørensen). The fan guides the polluted air from an intake vent through the filter unit before exiting the device with a lower particle count. Here, the device is placed on the Zhongshan Bridge. (Photo by David Garcia)

Another device tested how local algae could be integrated within facade systems to absorb air pollutants. Algae are a diverse group of aquatic photosynthetic organisms that absorb air pollutants such as carbon dioxide and nitrogen oxide during photosynthesis and grow while producing Oxygen. Algae was cultivated from water sources across Lanzhou and Lanzhou New Area (LNA) using a specially designed incubation unit and tested using a portable facade panel (Figure 28, 29 and 30) to see whether air pumped through these cultures had reduced levels of air pollution, both gas and particle. Air pumped through cultures containing algae had significantly increased air quality (Table 4), and cut both hazardous gas and particle content, leading to as much as an 89% reduction in particle pollution. The system was probed as an urban skin for outdoor and indoor spaces.

test	**aqi**	**pm10** µg/m³	**pm2.5** µg/m³	**pm1.0** µg/m³
not treated air	182	111	140	89
algae culturale 1	26	8	8	7
algae culturale 2	36	11	11	9
algae culturale 3	29	10	9	8
algae culturale 4	29	10	9	8

Table 4

Results from facade module filtration tests for air quality and particle content in 4 applications.

Figure 28

Device algae cultivation begins water sampling from the Yellow River, Lanzhou.

The architectural devices allowed data to be measured and established a visual clarity and hierarchy that manifested the details of complex phenomena, which could not otherwise be fully understood. They obtained a thorough understanding of the existing site conditions and the means to anticipate and explore architectural design solutions that cope with air pollution by restoring good air quality. The architectural device enabled the direct understanding and the visualisation of the local hyper-specific level of pollutions, thus supporting the exploration of more effective regenerative ideas. The campaign in China provided a platform to collaborate with local inhabitants and scientists in the conceptualisation of the devices and has been of inspiration for the development of local solutions.

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Figure 29

Testing took place indoors in a sealed room by a west-facing window at approximately 20°C. A particle reader and MQ-135 sensor connected to an Arduino board were inserted into a deflated, transparent balloon. Temperature, humidity, pm1.0, pm2.5, pm10 readings were taken. These readings provided an 'air profile' for the filtered air for a different type of cultures cultivated in Lanzhou (photo by David Garcia)

Figure 30

Portable algae filled facade attached to a local shop front in Lanzhou.

CASE STUDIES
OF REGENERATIVE DESIGN
From Principles to Realisation

Edited by

Emanuele Naboni
Lisanne Havinga

Chapter Cover Image - Monash University Student Accommodation

The Monash University Student Accommodation in Australia was developed using parametric modelling to mitigate overheating risk. In order to limit solar gains and ensure summer comfort in the building, sunshades were parametrically designed and optimised. Furthermore, a renewable energy system was integrated into the design, which is predicted to produce more energy than the building requires to operate every year.

Courtesy Jackson Clements Burrows Architects

CASE STUDIES OF REGENERATIVE DESIGN

Table of Contents

IMPLEMENTATION OF REGENERATIVE DESIGN IN PRACTICE

Lisanne Havinga *Eindhoven University of Technology (TU/e), the Netherlands*

The previous chapters have discussed the principles of regenerative design and its application in digital tools through the topics *'Climate and Energy', 'Carbon and Ecology',* and *'Human Well-being'.* These chapters have presented novel tools, workflows, and examples of their application. Instead, this chapter aims to showcase examples that are currently at the forefront of regenerative design in practice. Firstly, three well-known international examples are discussed, and subsequently, the case studies presented in this chapter are introduced.

GEELEN COUNTERFLOW

The office of Geelen Counterflow (see Figure 1 and 2), designed by Architecten en Bouwmeesters Roermond, is considered to be the most sustainable office buildings in the world, achieving a score of 99.94% according to the international BREEAM system. The structural elements of the building are made of solid timber elements (PEFC certified) from the Black Forest. These wall-, floor- and roof elements were prefabricated and assembled in a flexible and demountable way, as such promoting circular economy principles. The elements are not connected with glue or metal, instead, a timber dowel made of beech was used. The wooden elements meet the structural, insulation and fire protection requirements; no additional finishes or wall insulation is required. Instead of the positive carbon footprint of steel, concrete or bricks, it is estimated that this construction – made up of 1200 m3 wood – has a negative carbon footprint of 2400 tons. In addition, the office building is fitted with solar panels that generate 50% more energy than the building uses. Heating and cooling demand are met by two ground source heatpumps. Solar thermal panels are used to transfer heat to a hot water storage tank. Rainwater is used to flush toilets and surplus rainwater (in addition to the 10.000 liter storage) overflows to the municipal rainwater sewer to top up a nearby wetland. Bat boxes, bird nest boxes, insect hotels, natural pools and native plant flora were integrated into the landscaping.

Figure 1

Exterior of the Geelen Counterflow office. In the external wall, Accoya timber cladding was applied to protect the timber structure against weather influences Courtesy Geelen Counterflow © John Sondeyker

Figure 2

Interior of the Geelen Counterflow office. Three skylights aim to minimize the need for artificial light Courtesy Geelen Counterflow © Adam Mork

THE CIRCULAR BUILDING & THE PEOPLE'S PAVILION

For the purpose of the London Design Festival and the Dutch Design Week, Arup (in collaboration with other parties) developed two demonstration projects of circular economy implementation: '*The Circular Building*' and '*The People's Pavilion*'. The Circular Building (see Figure 3 and 5) was designed such that all building components could be disassembled and reused. Components were 'tagged' with a unique QR code containing information for the purpose of its reuse. In addition, the components are digitally linked to a BIM-model and a materials database. A high percentage of the materials and products used were sourced from recycled products. The People's Pavilion (see Figure 4 and 6) aimed to create a pavilion using 100% borrowed materials. Following the Dutch Design Week, the building was to be dismantled and the materials returned in their original state. As such, the pavilion attained a close to zero embodied carbon footprint. The challenge implied using construction techniques that do not rely on glue, screws or nails. For example, the columns were made up of 7 meter tall prefab concrete foundation piles, while cross bracing was created using steel rods from a demolished building. This unconventional construction method had to be thoroughly tested and validated to ensure its safety, which was done in collaboration with Eindhoven University of Technology.

Figure 3

The Circular Building at the London Design Festival 2016 © Arup

THE EDGE

The Edge in Amsterdam, the Netherlands, is also one of the most sustainable office buildings in the world. The Edge, however, stands out because of the data-driven smart technologies that are integrated in the building. The building tracks its users continuously and is fitted with some 28.000 sensors to do so. All employees are encouraged to use a smartphone app which allows them to interact with the building seamlessly. For example, the building recognizes the number plate of your car when you arrive and will automatically open the garage and guide you to an available parking spot. The building subsequently guides you to a free desk, as 2.500 employees share 1.000 desks to increase efficient use of the space. On days where fewer employees are expected, an entire section of the building may be closed off to further increase efficiency. Wherever you choose to sit down, the app knows your preferences for daylight and temperature, and will adjust the direct environment accordingly. Highly efficient LED panels placed throughout the ceiling are fitted with a range of motion, light, humidity, temperature and infrared sensors. There are robot security guards and robot vacuum cleaners.

Figure 4

The People's Pavilion at the Dutch Design Week 2017 © Arup

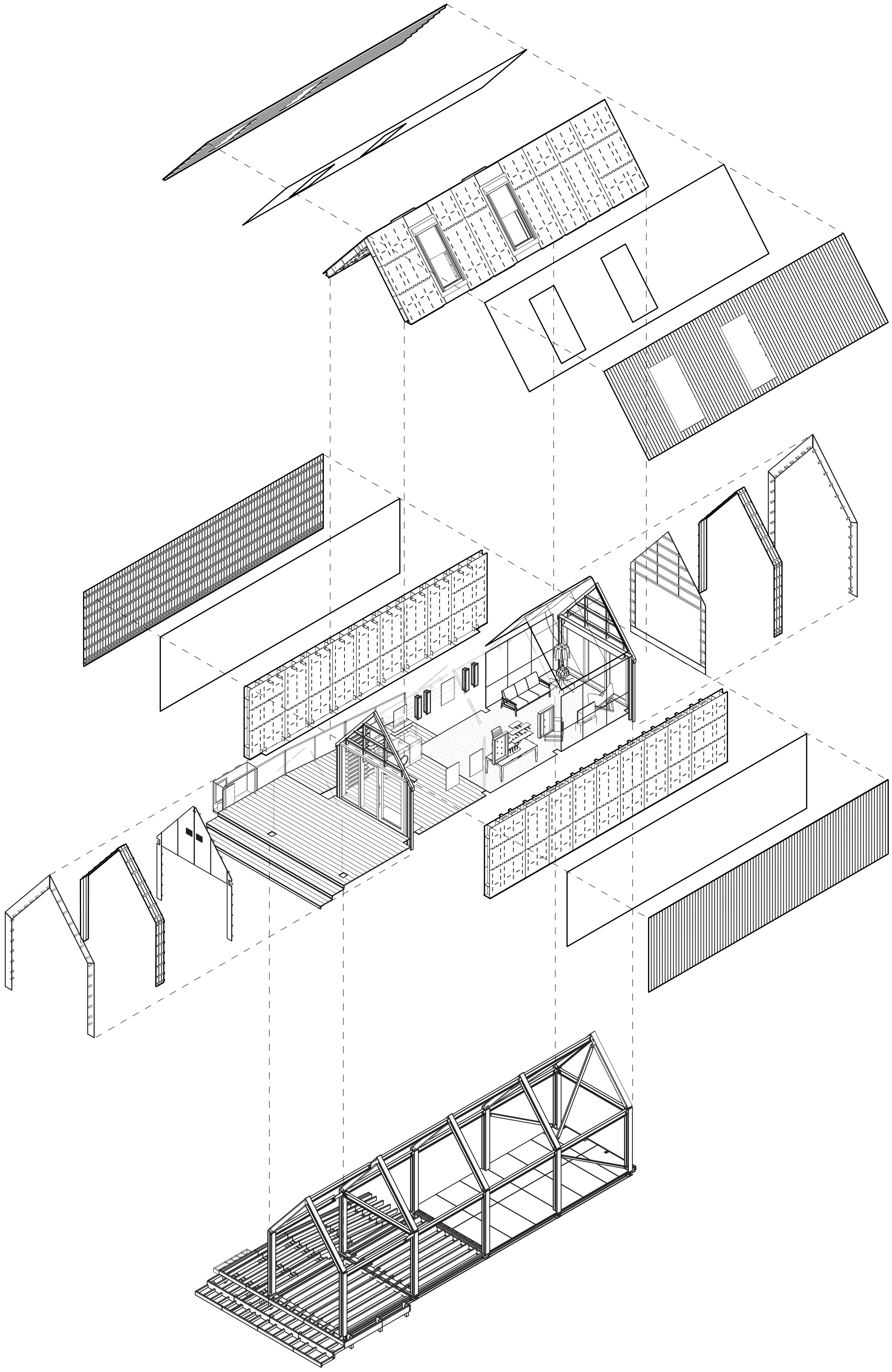

Figure 5
The Circular Building disassembly concept
© Arup

The app offers many social features: locate a colleague, schedule a workout session in the gym or select a dinner recipe allowing you to take home the fresh ingredients at the end of your workday. Every desk has a built in wireless charger. Some exercise stations in the on-site gym allow the building to harness energy from your workout. Sensors monitor the use of areas and bathrooms and inform the cleaning staff (and robots) about which areas should be cleaned when and how much. The next upgrade of the app will make sure the coffee machines know your preferred drink, and the desk manager knows your preferences for desk locations and comfort settings at different hours of the day. Many of these smart technologies are used to increase efficiency, but at the same time they increase the health and well-being of the employees.

CASE STUDIES

This chapter presents a range of case studies in which digital tools were used to implement regenerative deisgn. These case studies range from adaptive reuse to new construction, and from the scale level of the material to the neighbourhood.

Florencia Collo, Olivier Dambron and Rafael Alonso present an evaluation of the climatic performance of an intervention in which winter gardens were created by means of adding an external structure to an existing building. Sensors and digital simulation tools were used to quantify, evaluate and validate the climatic performance of the winter gardens and surveys were conducted to qualify the responses of occupants. The winter gardens act as an additional insulation layer by serving as a buffer area that reduces heat loss, infiltration and noise from the street. Meanwhile, they allow for solar gains, daylight and surrounding views.

Jonathan Natanian presents three brief examples of projects in which regenerative design principles were implemented. These principles range from urban farming through communal gardens, to optimized PV yield, to conscious material choices.

Both Juan Pablo Sepulveda Corradini and Herman Calleja present case studies in which parametric modelling was used to optimize comfort, daylighting, overheating and heating demand. As such, both contributions include – but are not limited to – the parametric optimisation of shading devices. Juan Pablo Sepulveda Corradini discusses the design of student accommodation in Australia, with a focus on overheating risk. Herman Calleja presents four case studies, two academic buildings (one in London and one in Paris), a Mediterranean village, and an exhibition centre in China.

Figure 6 (Next page)
The interior of the People's Pavilion at the Dutch Design Week 2017 reveals the purposely developed construction techniques to construct the building out of borrowed materials © Bureau SLA

Luca Finocchiaro presents two very distinct case studies. Firstly, the adaptive reuse of an old winery in Sicily is presented. The comfort and energy performance considerations are partly derived from the characteristics of the original vernacular architecture. In addition, reuse and recycling of materials plays an important role. Secondly, the ZEB Living Lab is presented, with ZEB standing for Zero Emission Buildings. The aim of the living lab was to prove that construction of a house able to produce more energy than it consumes every year was possible, even in Trondheim in Norway. For this purpose, the building relies on the integration of three renewable energy systems to cover its annual energy demand: a 12 kWp photovoltaic system on the roof, a solar thermal system in the south façade and a geothermal system connected to a heat pump on the north side of the building.

Martin Tamke, Mette Ramsgaard Thomsen, Paul Nicholas, Phil Ayres, Yuliya Sinke, Billie Faircloth and Ryan Welch evaluate the performance and behaviour of façade elements using Phase Change Materials. The evaluation is conducted using both a full scale prototype with embedded sensors, as well as simulation models with integrated machine learning techniques.

REGENERATIVE DESIGN IN PRACTICE

The recent report by the World Green Build Council is titled *'From Thousands to Billions'* [1]. In addition to the three extraordinary examples outlined in this introduction, this chapter presents some of the few examples of regenerative design in practice. Professionals working in the construction sector should strive to replicate and scale up these initiatives to ultimately attain a built environment with a net-zero – and at building scale positive – impact on the environment.

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IMPROVING CLIMATE AND WELL-BEING VIA WINTER GARDENS

Florencia Collo, Olivier Dambron, Rafael Alonso *Atmos Lab, United Kingdom*

For the past 30 years, the architectural practice of Lacaton-Vassal has been working with winter gardens as an integral part of several building programs. They have appropriated the technology of the agricultural greenhouses engineered to work with solar radiation, wind and sunlight, and of which the indoor thermal conditions are controlled with the use of geotextiles, adapted structures and nets. This research project, run in collaboration with the architects, aimed to gain a more precise understanding of the winter gardens' impact on the well-being of occupants. Sensors and digital simulation tools were used to quantify, evaluate and validate the climatic performance of the winter gardens and surveys were conducted to qualify the responses of occupants.

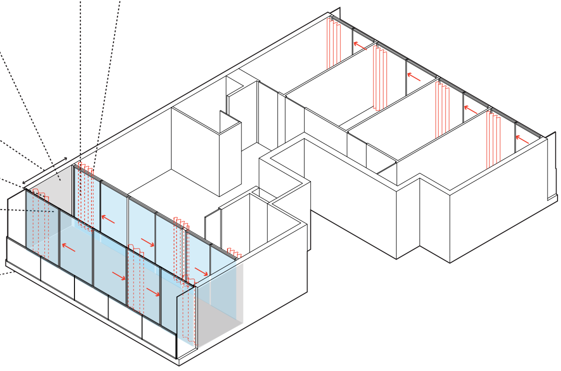
The architects´ philosophy is developed in Actitud [1]. Human thermal comfort and economic savings are the basis of all their projects: agricultural greenhouses offer large yet inexpensive envelopes that are considerably cheaper than those of traditional buildings. According to Lacaton-Vassal, *'from the moment you can offer double or triple the space (for the same price), houses can function in a non-uniform way: some areas are insulated and heated whereas some others are not, and these spaces can be combined'*. They report that winter gardens can be comfortable most of the year, depending on temperature, sun and rain. `

Their objective is to *'take advantage of outdoor conditions, domesticate them, manage them and transform them: the opposite attitude from an insulated space that defends itself from climate'*. Their residential schemes have spread across France in climates ranging from temperate to cold with warm seasons.

A recent example of the application of winter gardens is the transformation of a social housing complex in Bordeaux (see Figure 7). Spaces are wide and generous lofts where one can host trees and install furniture in non-predefined locations. The winter garden becomes a space of freedom where people are liberated from any precepts on how to furnish it (Figure 8).

Figure 7

Before (left) and after (right) photographs of the Mies van der Rohe 2019 award winning renovation of social housing in Bordeaux (Source: Lacton & Vassal, credits to Philippe Ruault)



concrete finishing
> to absorb the sun heat and
warm up the space even when
there is no more sun

regulated depth
> to heat up sufficient volume
of air and allow activities

solar curtain
> with a precisely calibrated opening and
reflection from greenhouses, to avoid
solar heat gain and allow daylight

large single glazing
> high light and sun transmission
> high infiltration to prevent the use
of the space as indoors

small balcony
> to prevent the high summer
sun to reach the wintergarden

large double glazing
> high transmission to allow sun and daylight
> low U value to insulate

thermal curtains
> very low U value to insulate in winter
> aluminium to reflect the sun in summer

Figure 8

Wintergardens are an additional space to the dwelling that can be freely designed by the users (Source: Lacton & Vassal, credits to Philippe Ruault)

WINTER GARDEN CONCEPT

The winter gardens' concept and composition are presented in Figure 9. The outer glazing covers the full façade length and often the entire envelope of a parent building that is also fully glazed. While the inner layer is double glazing with minimum U-value, maximum light and solar transmission, the external layer is either single glazing or corrugated polycarbonate and often permeable to air through slits. This configuration incites inhabitants not to consider the unheated space as part of the indoors, but as an explicit buffer zone. In front of the indoor glass, a thermal curtain with a U value of 1.0 insulates the living areas at night. The back of the curtain is made of aluminium, to be left 'ajar' during the hotter summer days, and reflects incident solar radiation. Before the winter garden glass, a permeable geotextile screen made of aluminium and polyolefin can be used to control solar access or privacy. Its opening ratio is project specific and depends on orientation and climate. The interior surfaces of the winter gardens are exposed concrete to take advantage of its thermal mass.

The environmental benefits that these systems offer are numerous, both for the parent building and for the inhabitants. They control thermodynamic exchanges with the outdoors and allow users to take advantage of the climate through daily and seasonal adaptability. Technically, they mitigate heat loss through multiple layering, but unlike traditional insulation, they allow in maximum solar gains and daylight while preserving the surrounding views and contact with nature. Regarding airflow, the winter gardens reduce infiltration towards the parent building by reducing wind pressure on the façade. Furthermore, a small opening during the cold period enables the renewal of fresh air from a naturally pre-conditioned space, which is more hygienic and healthier than the use of mechanical systems.

Figure 9

Design and composition of the winter garden concept

Regarding acoustics, winter gardens can halve incoming noise from the street. In winter, when both layers are closed, they function as buffer spaces. In summer, when the external layer is opened, the system becomes a deeper balcony shading the interior from the high sun and functions as a protected outdoor space. During the mid-season, mild temperatures inside allow the occupants to leave the inner layer open and use the area as an extension of the indoor space.

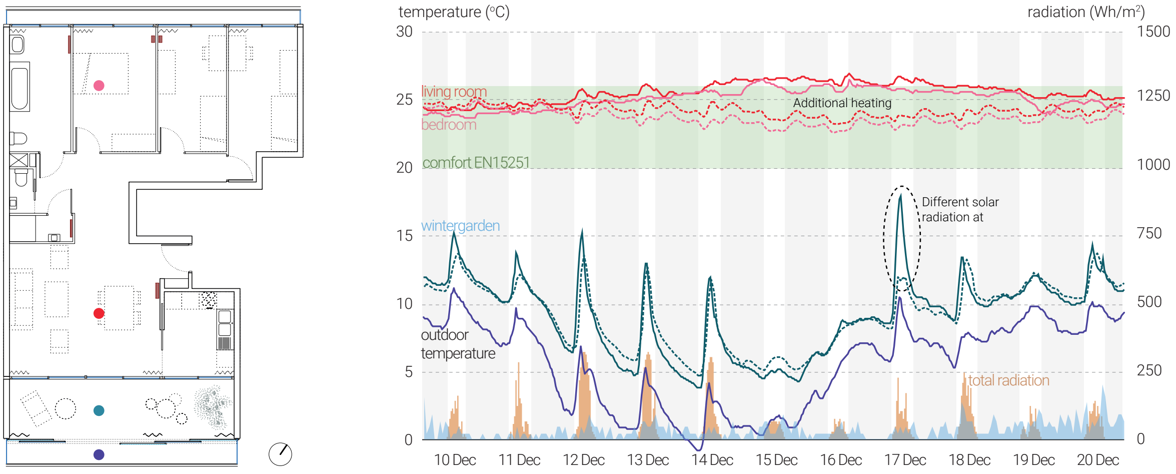


Figure 10

Plan of one of the units with datalogger placement (left), and it's measurement results (right). In solid line, measured temperature in two main rooms, winter garden and outdoors during 10 days of December (heating on). The dotted line shows the calibration of the model to the measurements. The pink and red lines indicate the reduced heating demand when introducing the winter garden.

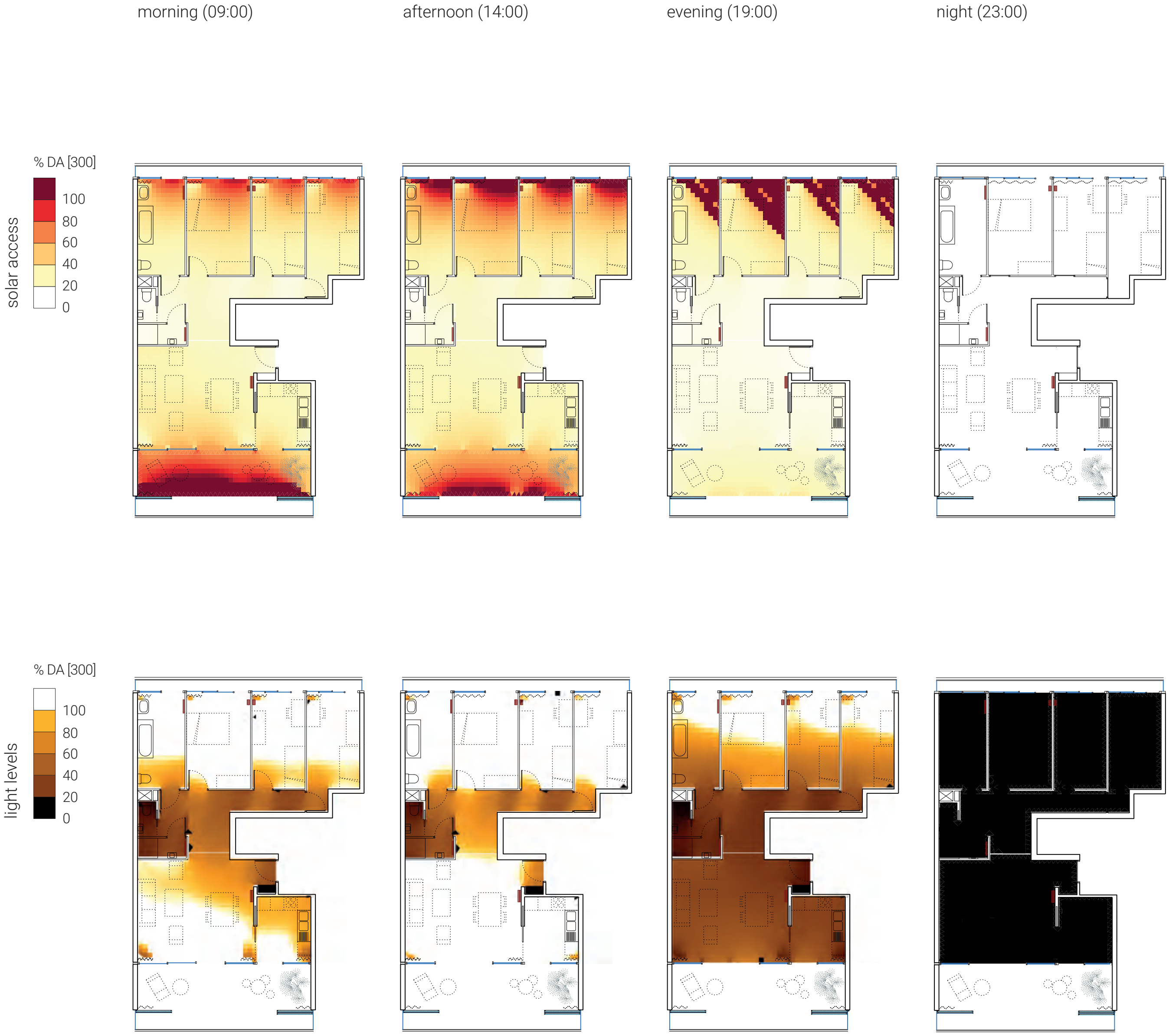
MICROCLIMATIC EVALUATION

The emerging web of analysis tools from Ladybugtools enables a more scientific exploration and more in-depth understanding of their performance. Four case studies are currently being re-studied that represent the typical situations of the architect's residential schemes: a housing complex, a detached tower, a refurbishment and a new building inside the urban fabric. This publication takes an example of the latter, which is located in Paris.

Dataloggers were placed in the main rooms to monitor temperature variations in December (Figure 10). Recorded data and hourly information about weather conditions during those days (outdoor temperature, solar radiation, wind speed and wind direction) were used to calibrate the computational model. The calibration reached a precision where the average temperature deviation in the winter garden was 0.5^{o}C, with a maximum of 2.0^{o}C. This procedure validates the 3d virtual model as it behaves such as reality and enables extrapolation of the results over the rest of the year. The assumption for indoor fresh air supply was a constant 120m^{3}, which corresponds to space permanently occupied by four people.

A microclimatic cartography was produced (Figure 11) to visualise environmental conditions across the seasons; covering solar access, light levels, airflow, and operative temperature. This resulted in a deeper understanding of the microclimate of each room and resulting interactions. It also enabled verification of occupants' feedback, such as the direct sun being the cause of overheating in the bedrooms during hot summer afternoons.

Figure 12 presents the evaluation of comfort, heating demand and daylighting. The space was assessed in passive mode in terms of daylight and thermal comfort against the European Standards EN15251 and EN17037. Results show that 80% of the space is in daylight autonomy (300 lux) with very bright levels inside. The living room remains in comfort 75% of the time and the bedrooms 61%. The winter garden has comfortable daytime temperatures during 6 months of the year, while during the other half temperatures depend on solar availability. Heating demand is very low with a setpoint of 19^{o}C (French regulator's setpoint - RT2012) and an average of 7KWh/m^{2}, and remains low if a more realistic setpoint of 23^{o}C is considered: the total energy demand would be around 20.3 KWh/m^{2}.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afternoon (14:00)
evening (19:00)
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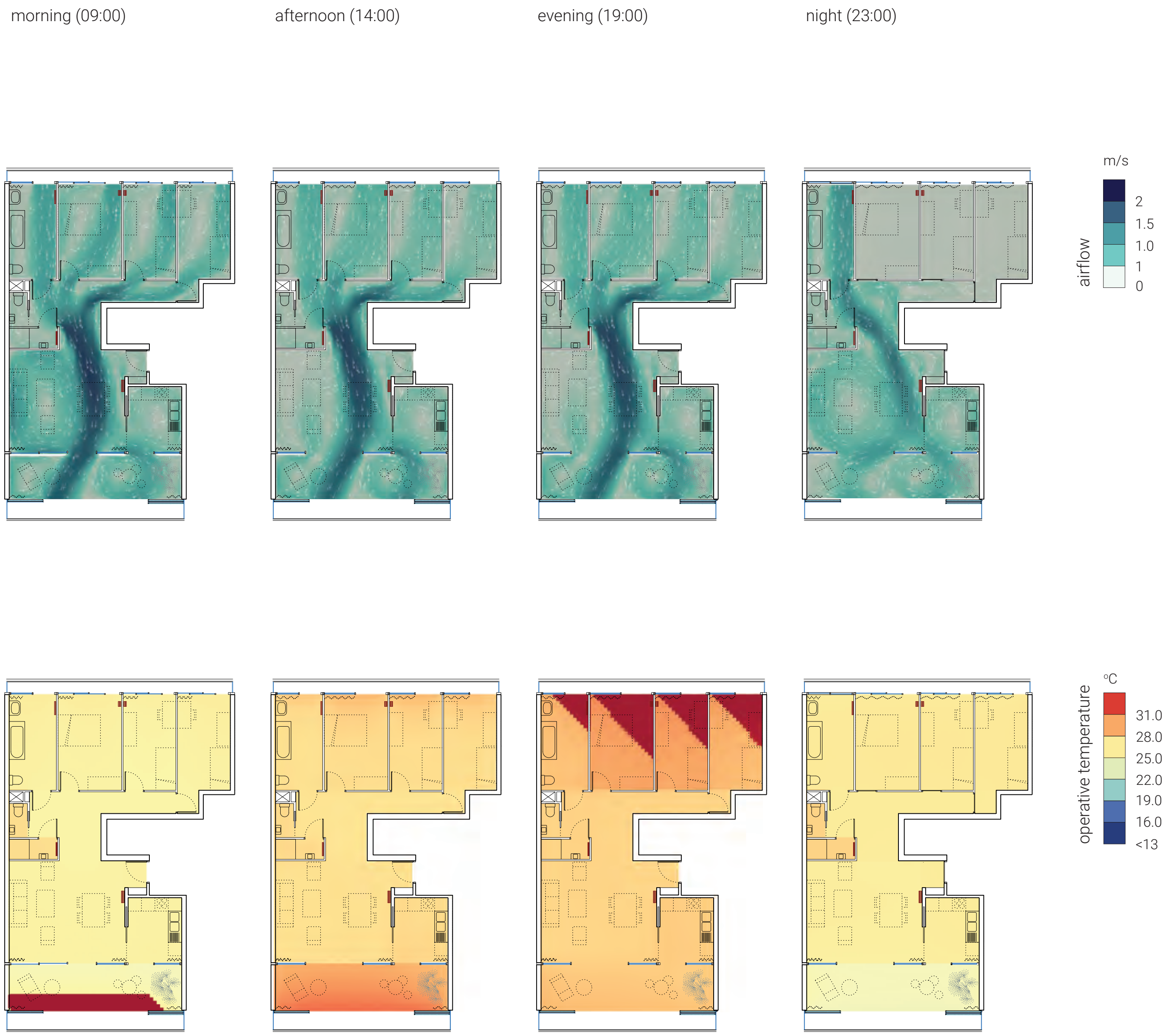

Figure 11

Microclimatic cartography of the apartment during a typical summer day. Different environmental parameters (solar access, light levels, airflow, and operative temperature) were scanned at 4 different hours of the day, and on average during a week

RESIDENTS’ EVALUATION

One of the main concerns developers and planners express about the system is its dependence on user behaviour. However, in all of the interviews conducted so far, 100% of the residents confirmed adjusting every element of the system to control their comfort indoors. Inhabitants have consistently reported that the winter garden was their favourite space, mainly due to environmental reasons, such as the very bright daylight levels inside (78% of the users), the fresh air (45%) and because it is simply nicer (45%). These reasons ‘outperformed’ practical ones such as ease of maintenance (11%), lack of space elsewhere (22%) and no precise reason (11%). A remarkable outcome from the interviews was that although occupants considered that some of the spaces were not in comfort all the time, they did not wish them to be different, which indicates the acceptance of the buffer space as such and a particular pride in the construction. The feedback proves that if the building is carefully designed, there is no reason not to rely on the users for climate adaptation, that interactions with climate are highly desirable for residents and that these schemes raise awareness of their microclimate.

All in all, Lacaton & Vassal´s winter gardens act not only as climate systems, but they also create more enjoyable indoor spaces that are bright, adaptable, comfortable and healthy across the seasons and that ultimately provide well-being, contact with nature and happiness to their occupants.

Figure 12

Top: Thermal performance of the two main rooms and winter garden in passive mode. Temperature was calculated at every hour of the year and contrasted with comfort conditions from EN15251. Middle: Space heating demand of every room with set points of 19 and 23°C. Bottom: Daylight Autonomy [300 lux] calculated at every point in space. The average Daylight Autonomy achieved is 80%.

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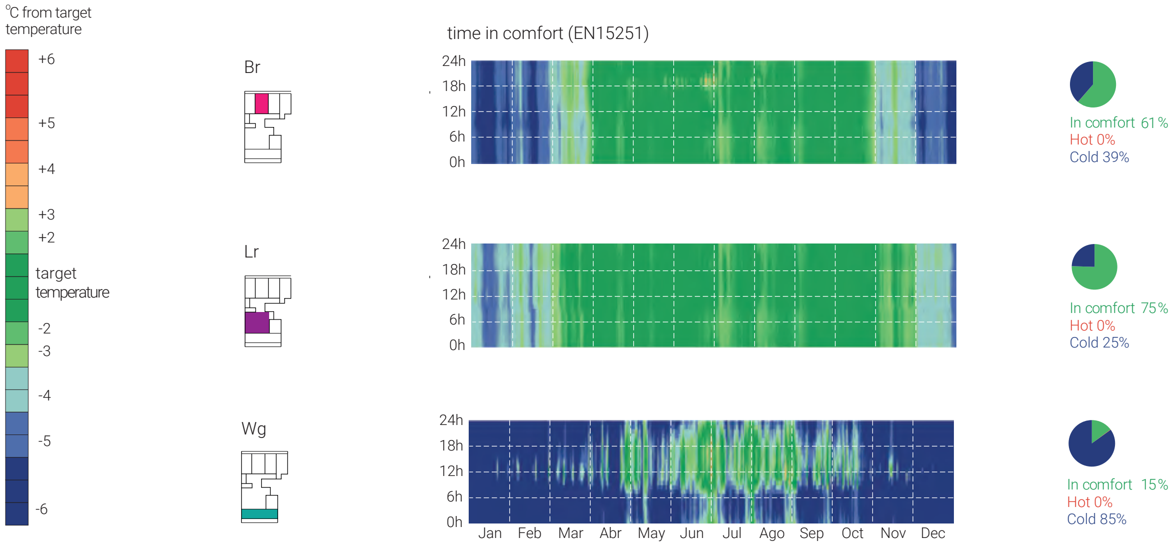
°C from target temperature
+6
+5
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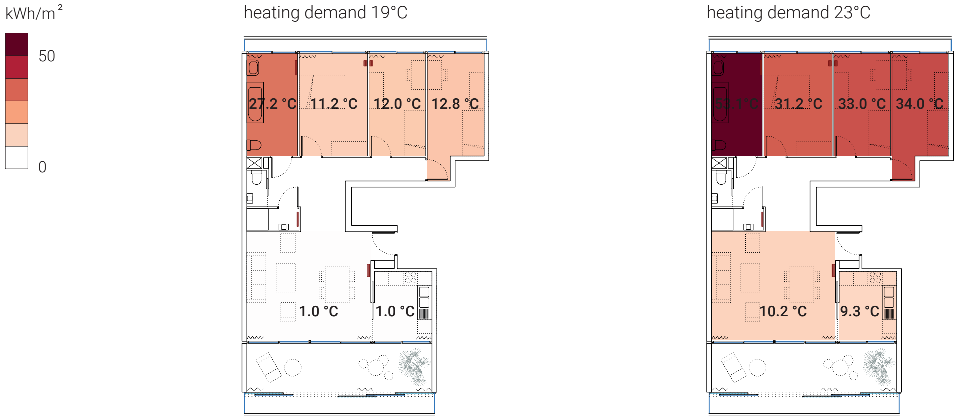
target temperature
-2
-3
-4
-5
-6
time in comfort (EN15251)
Br
Lr
Wg
24h
18h
12h
6h
0h
Jan
Feb
Mar
Abr
May
Jun
Jul
Ago
Sep
Oct
Nov
Dec
In comfort 61 %
Hot 0%
Cold 39%
In comfort 75%
Hot 0%
Cold 25%
In comfort 15%
Hot 0%
Cold 85%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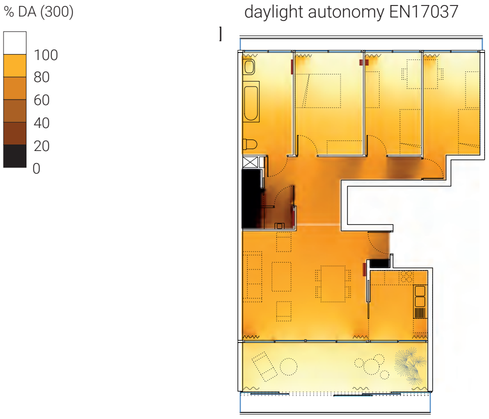
% DA (300)
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80
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0
daylight autonomy EN17037

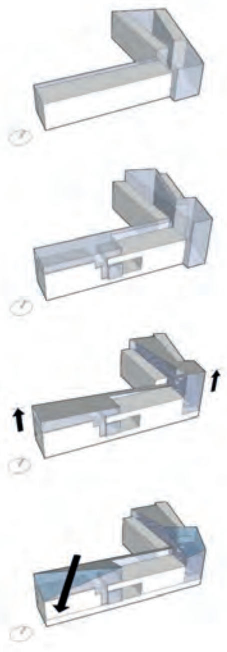
COMMUNAL AND BIOPHILIC PRINCIPLES IN REGENERATIVE PROJECTS

Jonathan Natanian *Technical University of Munich (TUM), Germany*

In October 2018, the Intergovernmental Panel on Climate Change (IPCC) made a global call for an unprecedented transition to a net zero carbon-built environment by 2050 to keep the global average temperature rise below 1.5 ºC [1]. Although it was not the first call for a comprehensive re-thinking of the design of buildings and cities towards sustainability, this time should be the long-awaited tipping point when design practices will be disrupted, leading to an environmentally responsive or, even better, regenerative future. Although climatic design has been around for thousands of years [2] and has been much discussed in its new 'green' version during the past decades, regeneration signifies a new threshold in which the paradox of sustainable development [3], aiming for less environmentally harmful processes or products, will be replaced by the regenerative idea of environmental improvement [4]. Although the regenerative design concept has been around for a few decades and is rapidly expanding nowadays with new standards such as the 'Living Building Challenge', its application is rare in practice and thus requires a paradigm shift [5]. In this context, this discussion seeks to showcase three examples of integrated regenerative thinking, in which simple concepts associated with community, ecology, biophilia, resource efficiency and environmental quality interacted and directly impacted the design brief and core values, as well as the buildings' morphology towards a new generative aesthetic quality.

Figure 13

Southwyck Co-Housing, Brixton, London. Jonathan Natanian, Juan Vallejo, Javier Guzman Dominguez



BRIXTON URBAN REGENERATION SCHEME

Figure 13 shows a redevelopment scheme for a district in Brixton, London, in which regenerative ideas drive the design strategy from the urban to the unit scale. The strong sense of community in the existing block, as well as the agricultural background of Brixton, inspired the application of urban farming as the key regeneration concept in a multi-scale approach throughout the project - from private to communal to public spaces. Following a detailed radiation analysis, building forms and outdoor spaces were shaped to support optimised energy and water harvesting. Landscape and vegetation programs were closely linked with the climatic design of the buildings, which in turn informed the internal layout design of the residential units. Through applying a holistic approach driven by a site-specific communal concept, several regenerative principals have been implemented including biophilia, climatic design and energy and water driven design, all under the larger goal of enhancing the existing social and communal fabric.

CO-LIVE TEL AVIV

The communal living concept for Tel Aviv (Figure 14) relies on the transformation of degraded brutalist buildings scattered around Tel Aviv's city centre by reconnecting them with contemporary urban living patterns. Focusing on the transformation of a specific building (Yachin), the design emphasises the diversity of spaces, uses and users, and establishes new hierarchies between private and public domains under the theme of a co-living organism. The energy strategy incorporates this theme in the design of a mutual energy hub for demand, supply and management. The new public street, which is envisioned as growing vertically across and above the building, creates a new green urban space for both the city and the tenants in which people can interact, grow food and work. The new wing includes a dynamic combination of residential units and communal gardens that can adapt according to the needs of the city. Adaptability, the reinvention of green areas, social cohesion, communal energy and renovation of the existing urban fabric were the core regenerative values, which echoed through the design outcome.

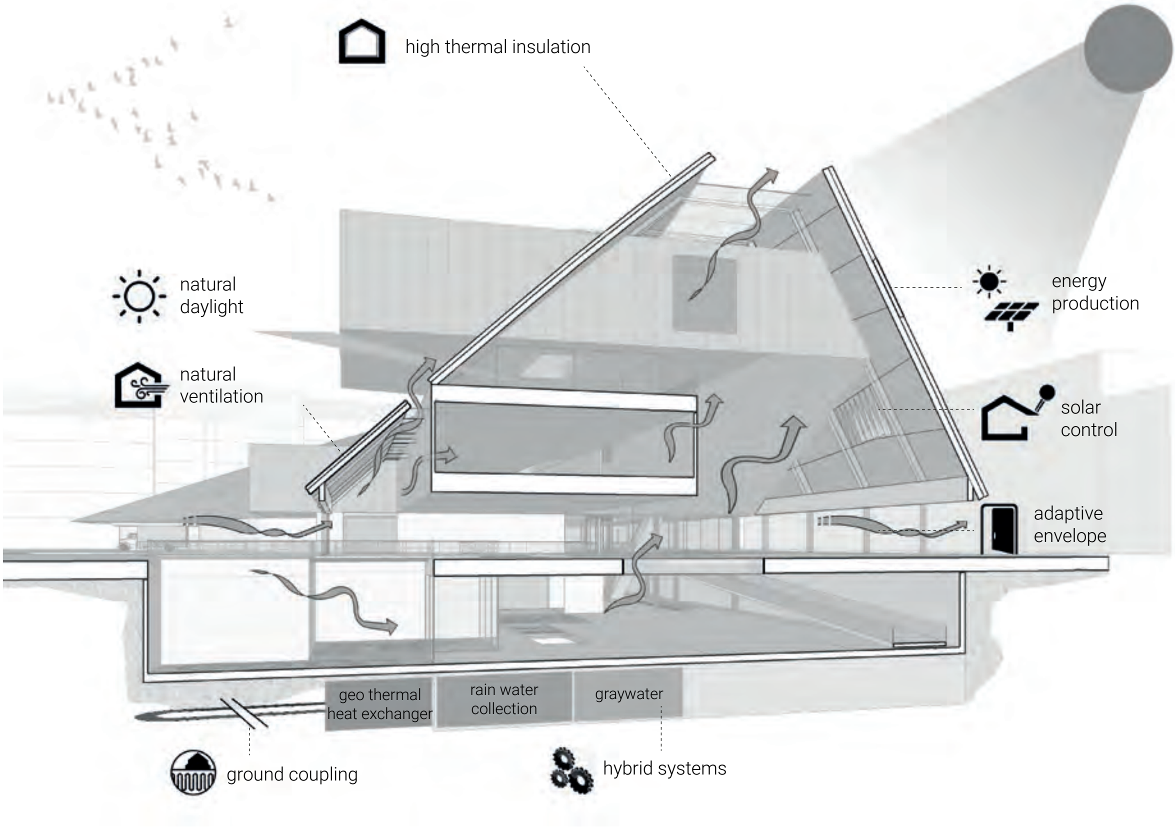
Figure 14

Design proposal for Tel Aviv's new urban residential forms competition. Jonathan Natanian, Ilan Balouka and Guy Verona

LIGET MUSEUM OF ETHNOGRAPHY

Reconnection with nature serves as a central design principal in the proposal for the Liget Museum of Ethnography (Figure 15) in Budapest, Hungary. The building is designed to be raised above the ground to allow a direct connection between the park, the museum's ground floor and the city. The use of traditional Hungarian thatching for the outer skin of the building reflects both for the ethnographic identity of the building as well as thermal, Life Cycle Assessment (LCA) and construction load considerations; the use of thatching results in light construction loads which enables the 'lifting' of the building skin and creates the desired connection between the building and its natural environment. The use of digital design tools helped optimise the form of the building for improved PV yield, reduced the use of materials and optimised daylight and ventilation performance. This case study demonstrates how a conceptual idea, an ethnographic image, in this case, can effectively drive a wide variety of qualitative and quantitative environmental concepts.

Figure 15
Liget Budapest - Museum of Ethnography design proposal. Jonathan Natanian and SO Architects



TOWARDS A REGENERATIVE ARCHITECTURAL LANGUAGE

In light of the urgent call for a paradigm shift in the architecture, engineering and construction (AEC) industries towards a holistic regenerative approach, the main challenge is to bring regenerative principals into the real-life design of buildings. The three examples here demonstrate how, during the design process, these principles could be easily intertwined in various win-win situations. For increased regenerative design implementation, raising awareness of these principals and their interdependencies is key. Thanks to new computational tools, e.g. BIM or Grasshopper, which are already popular among designers, regenerative principals can now be easily quantified and visualised during the design process and hence inform the decision-making process.

Perhaps as a next step, as soon as LCA accounting and building integrated energy production are more common practices globally, the technology-intensive challenges such as zero carbon, waste and water will become more feasible. The discussion of environmental design aesthetics will continue and expand from its 'green' phase to its regenerative future. The question of how buildings that offer energy efficiency, healthier conditions and well-being may look, could and should spark innovation and further push the boundaries of regenerative design.

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DESIGN TO MITIGATE OVERHEATING RISK IN AUSTRALIA

Juan Pablo Sepulveda Corradini *AECOM, Australia*

This section shows the implementation of Ladybug Tools in a design case where genetic algorithms are used to deal with multivariable optimisation. The case study is the Monash University Student Accommodation. The university has committed to reaching net zero carbon emissions by 2030, and from that date, regenerative targets may be implemented (such as energy positive outcomes). Monash stipulated that its new 150-room, 6-storey student accommodation (total floor area 5,100 sqm), to be located at its campus on the Mornington Peninsula, would implement two strategies. The first is to reduce energy demand by meeting the targets of the Passive House Standard (PHS). The second addresses energy production by incorporating rooftop renewable energy production. To fine-tune all these aspects and human health via daylighting quality, a Parametric Design workflow based on Ladybug Tools was used to find the fittest solution [1].

ADAPTING THE MASSING TO ADDRESS OVERHEATING

The Passive House concept is generally associated with cold climates as it emphasises the thermal envelope to reduce heat loss. For this reason, in hotter climates overheating can be a problem if not considered carefully. Preliminary analysis for the project revealed that the Passive House heating criteria would be relatively easy to meet in the Australian climate. However, overheating immediately appeared as an issue because of a second constraint:

- The solar radiation in this zone is 26% higher than in central Europe (Frankfurt).
- Kitchens were mandatory in every 18sqm room. Due to this constraint, internal heat gains in the initial architectural concept design were 250% higher than recommended by the Passive House Institute.

As the first response to these challenges, the initial architectural concept was reviewed: compactness of the volume was improved, and variable permeability was integrated to enable natural ventilation of the common spaces (e.g. to purge hot air at night).

Figure 17
Photograph of the realised building (Courtesy Jackson Clements Burrows Architects)

PARAMETRIC OPTIMISATION: EVOLUTIONARY ALGORITHMS

In order to limit solar gains and ensure summer comfort in the building, sunshades were parametrically designed and optimised to respond to the eight different orientations of the façades. This strategy was especially critical as the Daylight Autonomy criteria described in the Green Star (Australia Green Building certification) criteria led to two conflicting goals: limiting solar heat gain vs daylight autonomy. To streamline the design process with the design team, an iterative workflow to solve this problem was established.

First, the architect's original SketchUp file was converted to a Rhino-Grasshopper parametric optimisation script, and the Multi-Objective Optimisation approach (Pareto Frontier formula) was used to identify the pool of solutions for each of the architect's shading device proposals. Next, the fittest solutions per façade orientation were incorporated into the Passive House Planning Package (PHPP) to identify which solutions also met the PHS.

Figure 16 (Next page)
Photograph of the realised building (Courtesy Jackson Clements Burrows Architects)

To ensure that thermal comfort would be achieved in each room of the building, particularly in the students' rooms, an additional set of simulations was developed using the IES (Virtual Environment) multi-zone thermodynamic simulation tool, which provides more granular results. These results were then re-treated in a psychometric chart. The results illustrated that the rooms would remain in the thermal comfort zone all year-round if ceiling fans were installed in each student room.

THE OUTCOMES

The PHPP showed that the final design met the overheating criteria (>25°C less than 10% of the time) and achieved the Passive House Certification Standard. Heating needs are predicted to be three times below the PHS (5 kWh/m2.a). Furthermore, a renewable energy system (60kwp PV array) was integrated into the design, which is predicted to produce more energy than the building requires to operate every year. The multi-zone simulation results showed that thermal comfort was achieved 98% of the time in the most critical rooms per façade as the ceiling fans were able to reduce the thermal sensation by 3°C. Ultimately, a successfully adapted Passive House design to the Australian climate was developed, where the engineering and architectural strategies align with Monash University's Net Zero Carbon Emissions strategy. The building was realised in 2019 (see Figure 16 and 17).

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DAYLIGHT AND COMFORT THROUGH PARAMETRIC MODELLING

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chapmanbdsp and Architectural Association School of Architecture (AA), United Kingdom

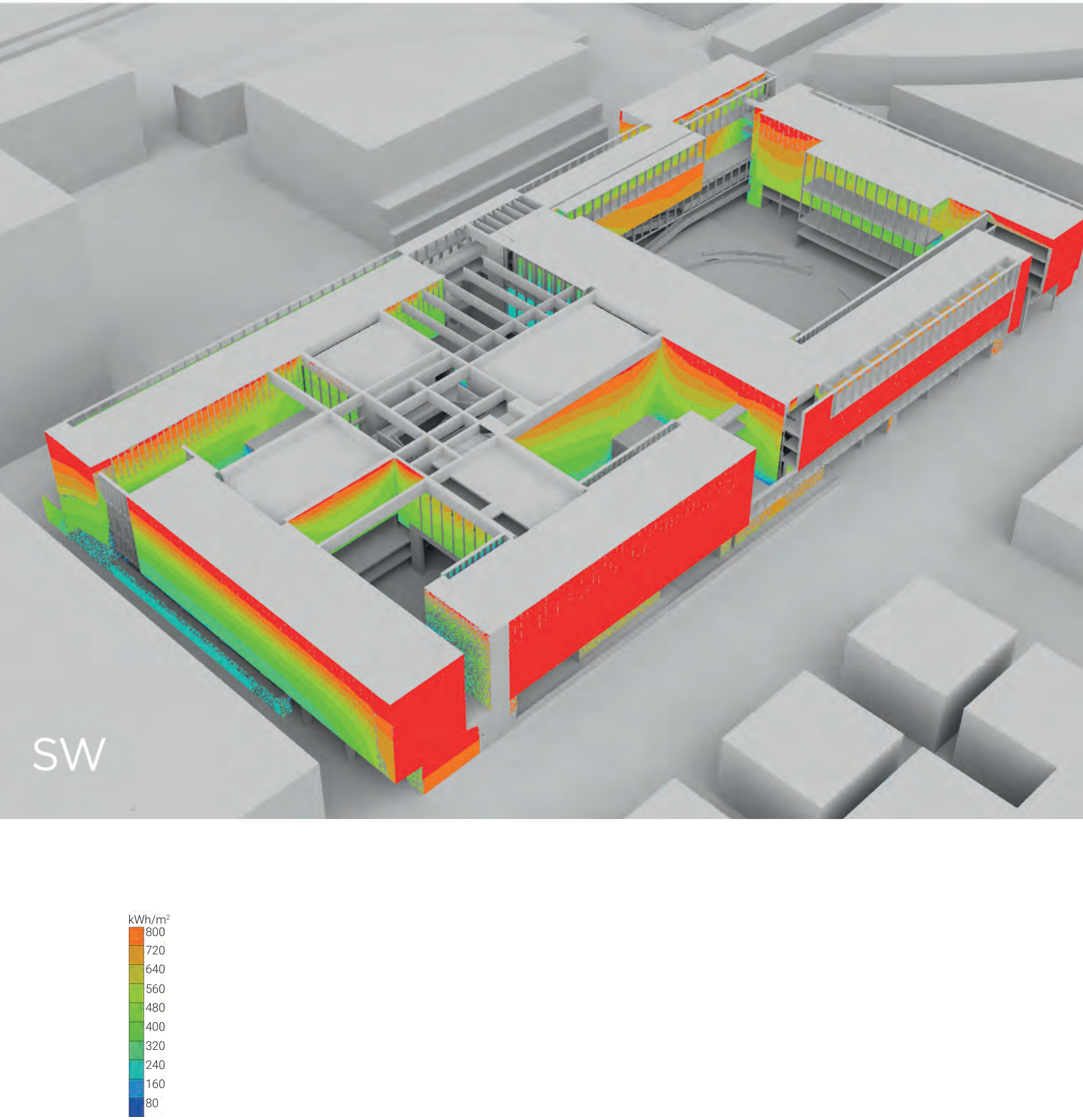
The application of parametric environmental design from an early stage during concept design provides the opportunity to inform the design team through multi-objective optimisation. An Information-assisted approach may be used to identify the range of solutions or morphology trends that are worth investigating further, thus serving as a guide to the team without being too restrictive with regards to optioneering (evaluating different options to solve a specific problem). The following article illustrates some of the examples of the application of parametric modelling at chapmanbdsp.

INSTITUT MINES TÉLÉCOM

One of the first cases where parametric environmental design was applied at chapmanbdsp was in the design process of Institut Mines Télécom with Grafton Architects (see Figure 18). This project targeted the new HQE Tertiary Buildings certification. Hence, it was required that 80% of the perimeter zone of the offices and classrooms had at least 0.7% and 1.2% daylight factor, respectively.

During the concept stage, a script was defined such that different room and shading morphologies could be generated and evaluated instantaneously with regards to the daylighting criteria in Radiance [1]. This approach led to a large number of simulations being carried out (see Figure 19), which provided advice to the architect with regards to shading depth and in some cases, to rooms repositioning.

Figure 18 (Next page)
Design model of Institut Mines Télécom (Courtesy of Grafton Architects)


SW
kWh/m²
800
720
640
560
480
400
320
240
160
80

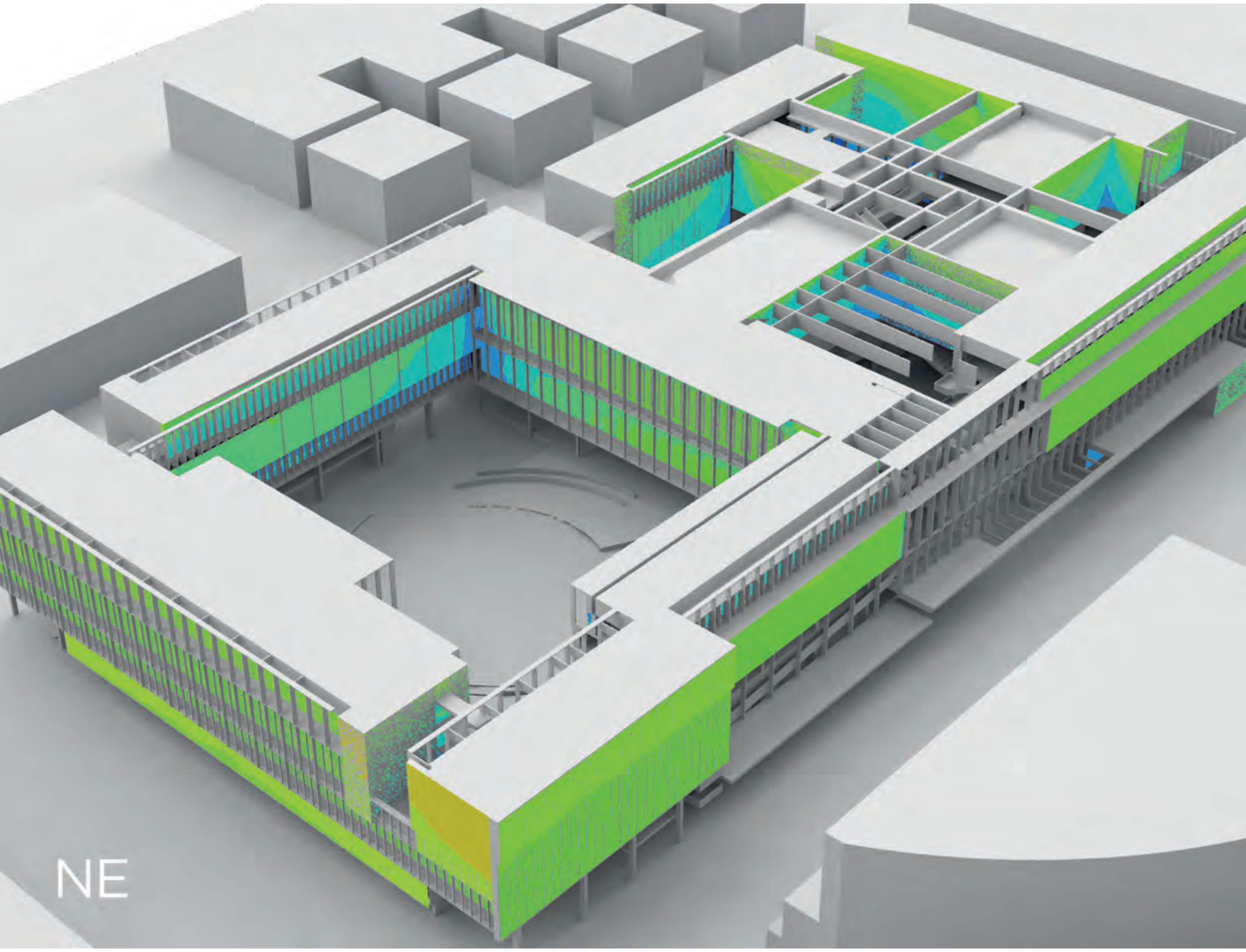


Figure 19

Façade annual solar radiation mapping of Institut Mines Télécom helped to identify the façades' exposure and areas that may require additional studies (Courtesy of chapmanbdsp)

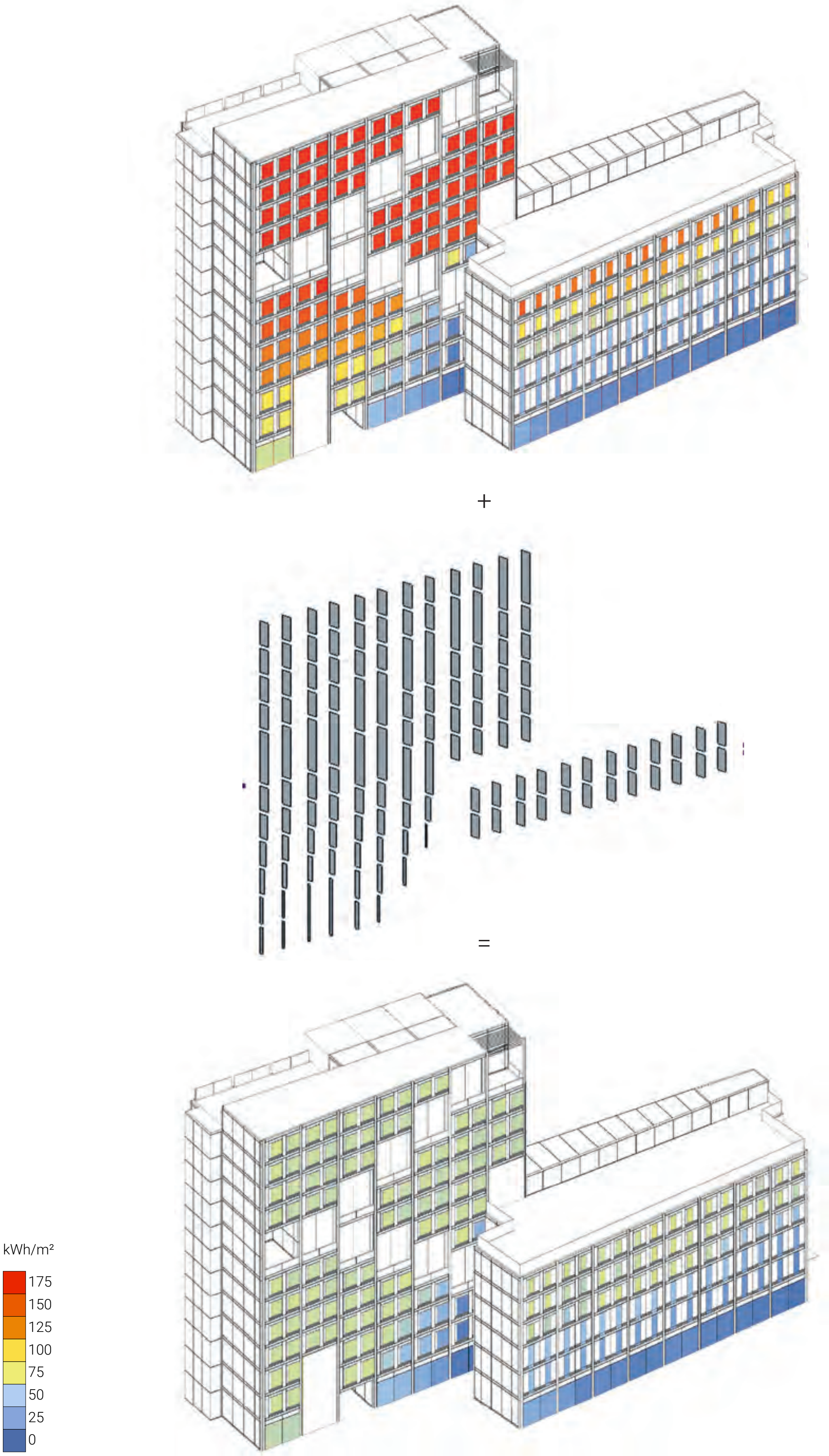

+
=
kWh/m²
175
150
125
100
75
50
25
0

Figure 20

LSE CBR façade solar control optimisation based on the received solar radiation using the Grasshopper Galapagos evolutionary solver. The algorithm used allowed for the vertical fin depth to be optimised based on the resulting irradiance mapping. The image illustrates the resulting façade solar radiation on the façade for the scenario without the vertical fins and the scenario with the optimised vertical fins. The recommended amount for a low overheating risk is <75 kWh/m^2 (Courtesy of chapmanbdsp)

LONDON SCHOOL OF ECONOMICS CENTRAL BUILDING REDEVELOPMENT

On the London School of Economics Central Building Redevelopment (CBR) with Rogers Stirk Harbour + Partners, parametric modelling was used from an early concept stage by chapmanbdsp. The project concerns an academic and teaching building in central London. An analysis was conducted to explore what shading strategy may allow for the design of cooling-free, naturally ventilated offices.

The assessment of spaces through dynamic thermal modelling allowed the team to identify how much solar radiation could be tolerated without producing overheating risk, in line with the CIBSE TM52 thermal comfort assessment [2]. This methodology is based on the EN 15251 adaptive comfort band criteria, which is applicable to assess the expected comfort conditions in naturally ventilated indoor spaces.

Using the resulting solar radiation threshold, parametric modelling through the Grasshopper platform was carried out to optimise the design of shading devices to reduce overheating risk with the minimum use of materials (see Figure 20). This resulted in a west façade with varying shading fin depth, thereby allowing the more sheltered lower offices to achieve adequate day-lighting levels.

The use of parametric modelling allows for the exploration of different design solutions through multi-objective optimisation. Through this approach, instead of having one environmental aspect optimised, the design research explores solutions which satisfy multiple environmental criteria that at times may have conflicting requirements, such as daylighting and thermal comfort. Tom Wiscombe uses the analogy that the best-fit species may not be the fastest or strongest but have a good performance in multiple aspects [3].

MEDITERRANEAN VILLAGE

A multi-optimisation study was also conducted recently by chapmanbdsp for a Mediterranean project with Foster + Partners where the reinterpretation of the local projecting balcony and loggia were used as an architectural language that provided both spaces for outdoor living and solar shading. In the study both the number of hours that mechanical cooling is not required and the percentage of hours for which artificial daylighting is not required were assessed using EnergyPlus and Radiance-based DAYSIM, respectively, through Ladybug Tools [4].

The analysis was carried out for four different orientations, considering five different obstruction ratios, such that five different ranges of applicable solutions were provided for each orientation. The same study was conducted for loggias and projecting balconies. Subsequently, a strong correlation was found between the solar radiation received on the façade and the pattern of overheating risk. A similar correlation was also investigated between the sky view factor and daylighting availability. However, these results were less accurate. Each façade was then assigned a colour according to the level of solar exposure to assist the design team with regards to the façade articulation (Figure 21).

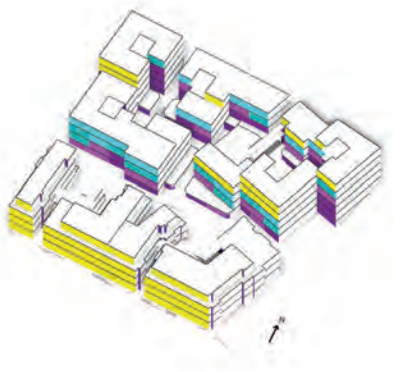


Figure 21

Matrices were developed to illustrate a 'palette' of recommended solutions with varying glazing ratios and projecting overhangs for different orientations and levels of exposure. The study was generated through dynamic thermal simulation and climate-based daylight modelling in Ladybug. The image shows the south and west facade recommendations, colour coded according to the level of solar exposure to assist the design team (Courtesy of chapmanbdsp)

SHENZHEN EXHIBITION CENTRE

The use of parametric modelling has also assisted the team at chapmanbdsp to investigate the expected thermal comfort performance with a more accurate resolution provided with dynamic thermal modelling (DTM) software. This approach was adopted in the assessment of a long linear semi-outdoor space in Shenzhen. DTM tools only provide the mean radiant temperature at the centre of the thermal zone. In order to get a higher resolution of the thermal comfort conditions in different areas of a cross-section in the space, the team at chapmanbdsp extracted the surface temperatures from the DTM tool and then used an in-house ray-tracing methodology that allowed the mapping of the mean radiant temperature at a much higher resolution allowing for a more accurate UTCI assessment of the different areas (see Figure 22).

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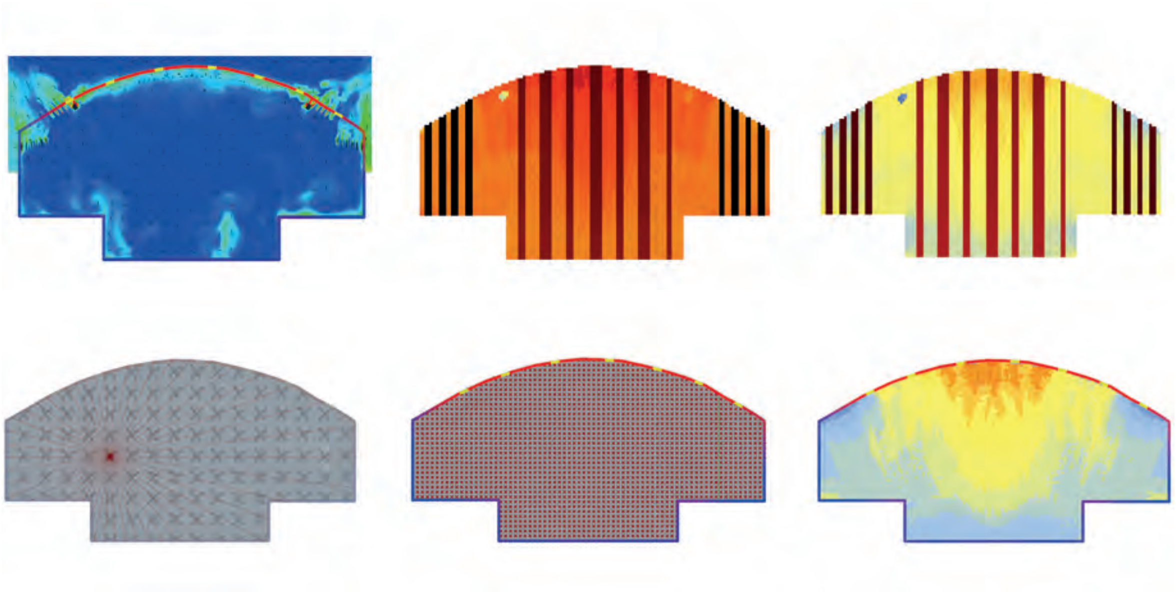
Figure 22

The result of the ray-tracing script developed to assess the mean radiant temperature at any point in the space in order to provide a high-resolution occupant comfort map that is not provided by commercial thermal modelling tools (Courtesy of chapmanbdsp)



REGENERATIVE ADAPTIVE REUSE AND NEW CONSTRUCTION EXAMPLES

Luca Finocchiaro *Norwegian University of Science and Technology (NTNU), Norway*

Regenerative design principles require a radical change in the way green buildings are designed and produced to integrate concerns related to humans and their relation to natural ecosystems. According to these principles, architects cannot only limit the environmental impact of their proposals; they must also understand how each project could positively contribute to the development of site and context [1]. This requirement indeed presumes a new set of analyses that go beyond energy efficiency to include concerns related to materials, water cycle, human health and well-being. Adjusting building form and construction to climate and context - according to climate adaptive design principles - represents, in this regard, a fundamental tool for exploiting regenerative design principles. The following projects demonstrate how climate adaptive design has been combined with actions to reduce the building environmental impact in a life cycle perspective.

Figure 23

A building bioclimatic chart in the Mediterranean climatic context underlines the potential for passive solar heating systems, natural ventilation strategies in combination with thermal mass (data elaborated using climatic data in the context of Catania, Sicily) (Adapted from [2])

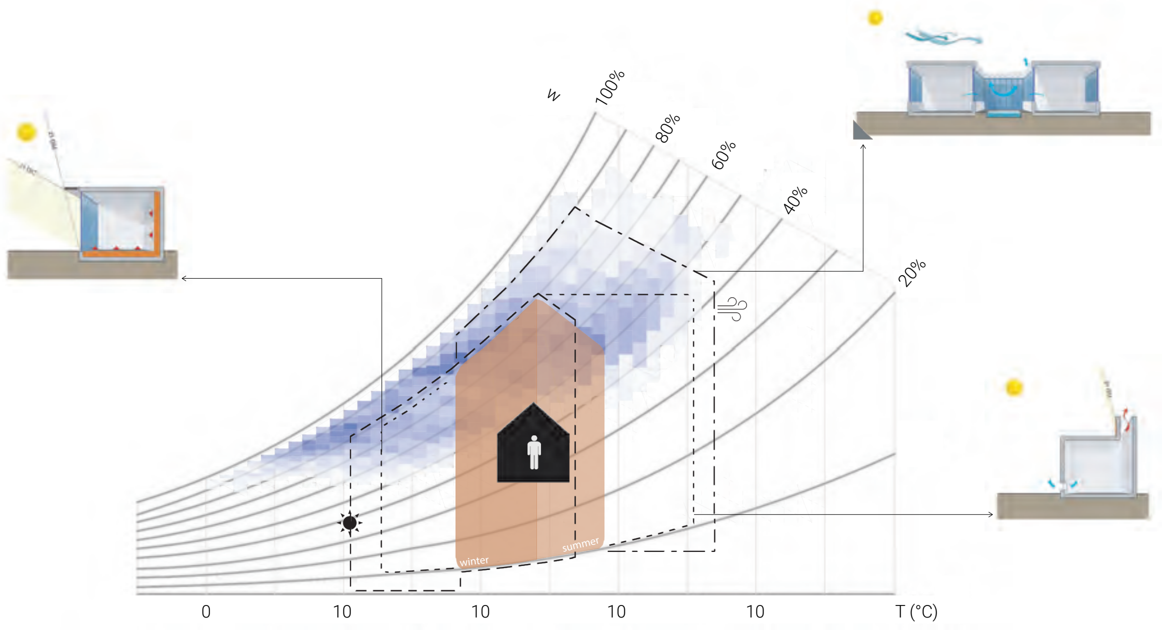
REFURBISHING AN OLD WINERY IN SICILY

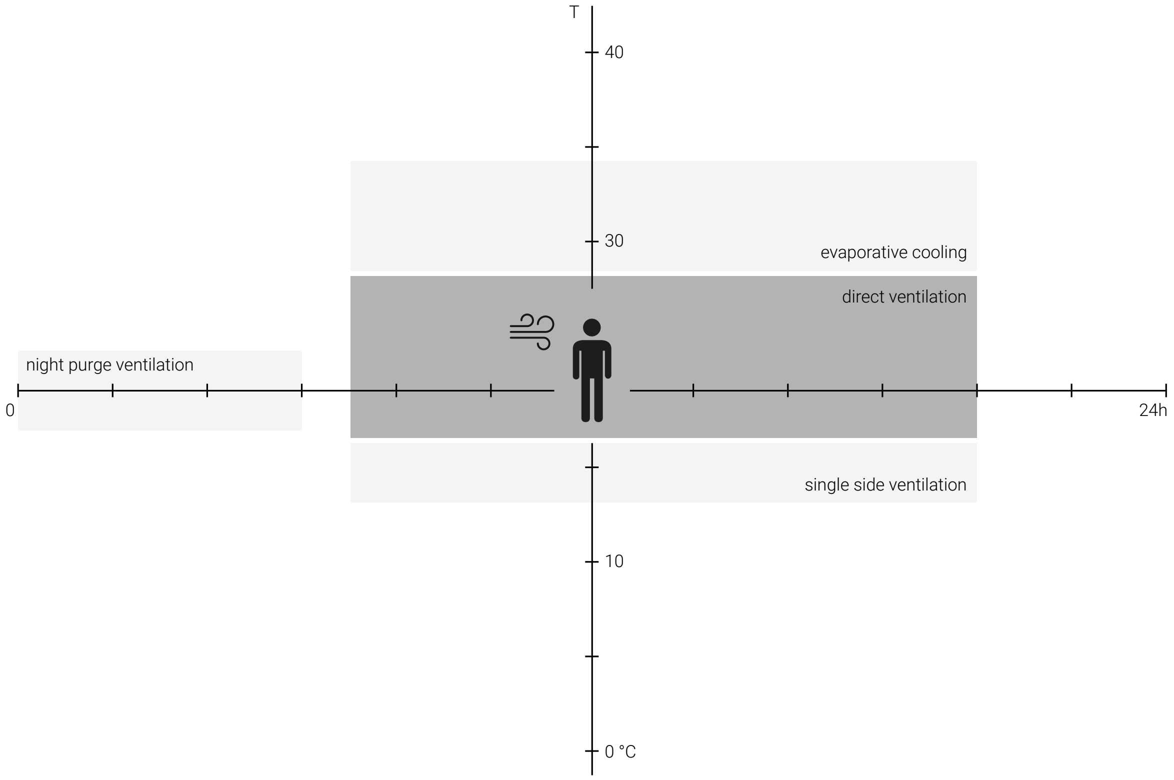
Historical buildings or vernacular architectures represent the result of an evolutionary process in which building morphology and construction have been continuously refined to provide proper environmental conditions in their interior. For this reason, these buildings are often characterised by inherent qualities that make it possible to convert them into highly energy efficient buildings.

A bioclimatic building chart, elaborated according to Givoni-Milne [2] for the Mediterranean climate (Figure 23) suggests a massive construction and the use of passive strategies, such as natural ventilation and passive solar heating systems, as the most effective solutions in this climatic context. Courtyards can also play an essential role in the buildings´ environmental performance because they can create specific microclimates that can markedly differ from the regular outdoor climatic conditions.

Figure 24

A conceptual diagram about the potential of different natural ventilation strategies in the Mediterranean climatic context edited thanks to state of the art research (2-10) on natural ventilation in the Mediterranean climate


w
100%
80%
60%
40%
20%
winter
summer
0
10
10
10
10
T (°C)


T
40
30
10
0 °C
0
24h
evaporative cooling
direct ventilation
night purge ventilation
single side ventilation

These principles are reflected in the form and construction of an old winery in Sicily, today under restoration after over 50 years of abandonment. The developed project did not aim to restore the building to its original conditions but rather to recognise those characteristics of the structure that could be further enhanced with modern technologies, such as thermally activating building components and inserting hand-driven valves for natural ventilation. The stone walls, of a thickness between 50 and 70 cm, were preserved while a set of natural ventilation strategies was implemented. Current research [2-10] recommends natural ventilation strategies that can be used depending on different outdoor conditions (Figure 24). A naturally ventilated gap of around 25 cm in height was achieved by excavating half a meter below the existing floor, while *arsenes* at ceiling height facilitate stack ventilation to extract exhausted air. Valves, regulating the amount of air removed, are connected to a south-oriented chimney, where a solar thermal system is integrated. The chimney aims to extract enough air to limit condensation phenomena that might be caused by the use of the floor as a cooling system.

The wooden floor, made from disassembled barrels purchased in a nearby winery (Figure 25), was glued over a 10 cm thick thermally activated layer of concrete. This was coupled with an air to water heat pump able to provide air at an adequate temperature for heating or to cool the building and was connected to a south-oriented solar thermal system (Figure 26). During summertime, cold water from the cistern is sent to the radiator floor for cooling purposes. A temperature of circa 17 degrees is controlled through the heat pump running on electricity provided by an integrated photovoltaic system.

New service cores were built that aligned doors in a way to facilitate natural ventilation and views towards the garden outside. The new service cores were built using, in large part, materials derived from the disassembly of the old service cores and recovered material from other minor demolitions throughout the building. Recycled old bricks were coupled with porous bricks, characterised by lower thermal transmittance, on the inner side with a layer of wood fibre insulation in between. This layer aims to limit heat losses in the winter while still ensuring a buffering of temperature fluctuations daily. Windows and doors were substituted with new handmade ones, produced with local chestnut from Mount Etna, and were equipped with double glazing filled with argon gas.

Figure 25

Five barrels of 5000 litres and 2,4 meters diameter was disassembled to provide enough material for the wooden floor. Elements were cut in a way to minimize waste.

Figure 26

A section of the building showing the integrated systems for enhancing the environmental performance of the existing structure.


electricity from pv
exhaust air out
hot water from solar thermal
valve
70 cm masonry wall
hp
ventilated gap
cooling mode
cistern

A reasoned use of local materials and advanced technologies for energy efficiency aimed to exploit the potential of inherent qualities of the building while still ensuring a tight connection with site and context at different scales (materials, form, environmental attributes). A building able to exploit natural ventilation systems and provide a tighter visual connection with the outdoor environment aims to give inhabitants a healthy and comfortable environment, which is in agreement with regenerative design principles.

Figure 27
Environmental concept of the ZEB Living Lab

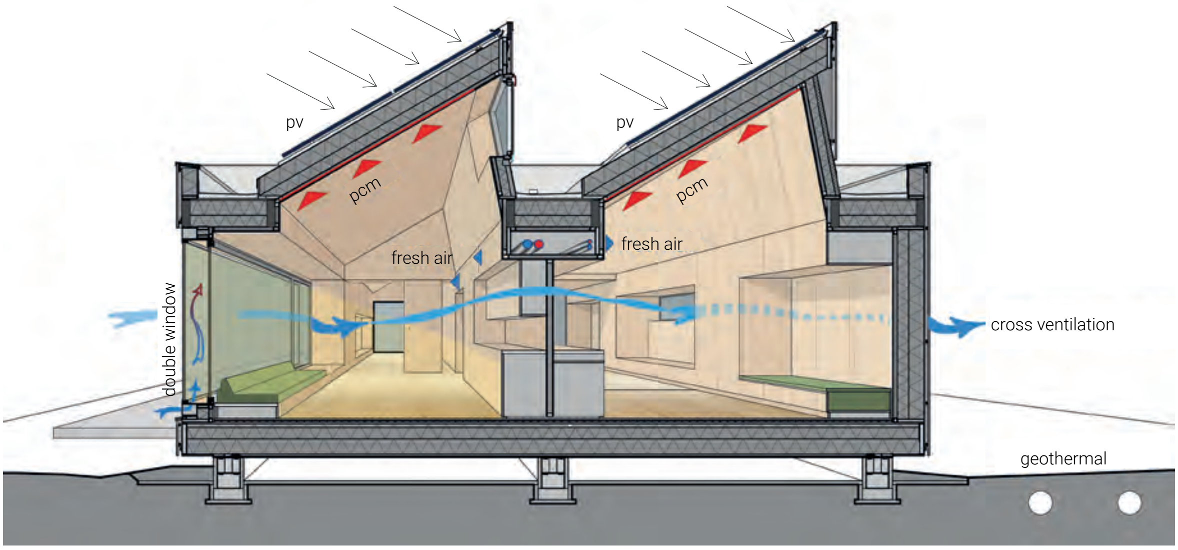
THE ZEB LIVING LAB.

The ZEB LivingLab (ZEB stands for Zero Emission Buildings)(see Figure 27, 28, 29 and 30) is the result of a complex multidisciplinary design process in which students, researchers and industry partners collaborated in the architectural design of a solar-powered house able to produce more energy than it consumes every year. The building concept (see Figure 27) was chosen as the result of a competition run in the first semester of the MSc programme in Sustainable Architecture at NTNU. The LivingLab relies on the integration of three renewable energy systems to cover its annual energy demand: a 12 kWp photovoltaic system on the roof, a solar thermal system in the south façade and a geothermal system connected to a heat pump on the north side of the building. Its construction aimed to demonstrate that ZEB targets could be achieved in the climatic context of Trondheim. Also, the building serves today as a laboratory to investigate users' interaction with state-of-the-art technologies for carbon neutrality. For this reason, it has been equipped with a data acquisition system able to record any information related to environmental performance and energy flow.

Figure 28
The interior of the ZEB Living Lab © Geir Mogen

The construction of the Living Lab optimised through simulations in SIMIEN and RADIANCE [11] for thermal and daylight analyses, respectively, resulted in a low-transmittance envelope with a glass ratio of circa 20%. Walls, floor and roof are all made of a double layer of Rockwool insulation with a total thickness of 45 cm. All windows in the house respect the passive house standards with an overall transmittance of 0,8 W/m^{2}K. The double window towards the south, designed as a passive solar heating system, is characterised by a markedly low u-value, varying from 0,65 to 0,69 depending on the ventilation rate within the air cavity. Because of the light construction of the building, however, solar gains might be responsible for large temperature fluctuations and overheating issues in the summer period.

Figure 29 (Next page)
The ZEB Living Lab at the campus © Geir Mogen


pv
pcm
pv
pcm
fresh air
fresh air
double window
cross ventilation
geothermal

For this reason, both south and north windows are coupled with an automated control system able to activate, when required, a natural ventilation flow through the building. Skylights facing north can be opened independently to let the exhaust air out through stack ventilation. PCM panels integrated into the ceiling construction aim to stabilise temperature fluctuations within the comfort zone.

Figure 30
Roof detail of the ZEB Living Lab © Geir Mogen

While optimising environmental performance, embodied emissions in materials were estimated using data elaborated by the ZEB research centre on a theoretical shoebox model, characterised by the same construction system [12]. Alternative photovoltaic systems were tested to offset the total environmental impact of the building. A two-slab solution of 6 kWp each was chosen as the best solution. According to simulations run in PVSyst, such a system would guarantee energy production of 6829 kWh between May and November, enough to offset - in combination with other renewable energy systems - emissions due to operation and materials used in the building [11].

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SENSORS, SIMULATIONS AND PROTOTYPING PCM PANELS

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KADK Copenhagen, Denmark
Billie Faircloth, Ryan Welch
Kieran Timberlake Architects, United States

Regenerative design implies the development of new technologies that are finely tuned to climatic cycles in order to reduce and produce energy for operation while managing outdoor and indoor thermal comfort. The project presented here displays and demonstrates an integrative modelling and design approach where orchestrating handshakes and feedback loops between disparate spatial and temporal domains led to defining a cogent design framework for practices that are trans-scalar, trans-temporal, and trans-disciplinary.

In more detail, this project examines the behaviour and design of geometries associated with Phase Change Materials (PCM) by constructing a prototype that is coupled to a mechanistic modelling interface. The prototype was mounted on an adjustable outdoor testbed in KADK campus, in Copenhagen. Its baseline geometry was continuously monitored and characterised concerning variation in liquid and solid states. The mechanistic model, which uses a finite element method, incorporates multiple components including geometry, orientation, material properties, context geometry (e.g. buildings and vegetation), weather, climate, and an array of sensors monitoring the real-time temperature distribution of the testbed and phase-change materials. Data were continuously collected from the testbed and used to calibrate, validate, and verify the model. In turn, the calibrated mechanistic model provided a platform for the future design of regenerative façade technologies.

MODELLING COMPLEX THERMAL BEHAVIOURS

The architectural design community has difficulty integrating methods to manipulate, measure, and model transient phenomena associated with open thermodynamic systems. Phase transition, such as the melting from solid to liquid, is one of these observable phenomena. It is influenced by the nuanced interaction between geometry, context, material properties, weather, and the mechanisms of heat transfer. Whereas the assumption of steady-state conditions provides a well-defined system boundary to study heat transfer; and, whereas numerical and analytical approaches, such as finite element analysis (FEA), discretize heat flow at an unlimited number of points across a given domain in order to identify boundary conditions; these methods are associated with multiple scales and disciplinary-specific workflows [1].

They are limited in their capacity to handle dynamic information flows, presume an analytic, rather than generative, design approach, and are indicative of a complex, multi-scalar, and multi-method modelling and simulation challenge within the design community [2]. Actual material behaviour is an entanglement of macro and micro-interactions and extensive and intensive properties across spatial and temporal domains [3]. For instance, architectural material assemblies continuously accumulate and dissipate heat, which engenders small, large, symmetrical, and asymmetrical thermal gradients. Thermal gradients, which are likewise a transient phenomenon, are attributable to the interaction between environment, material properties, local surface features, surface geometry, and overall form.

There is, thus, the potential to investigate a multi-scalar, multi-method design and modelling approach for architectural assemblies using methods from the fields of architectural design, thermodynamics, and materials engineering in which (1) using full-scale prototypes, the actual thermal behaviour of a material system is continuously measured and characterized; (2) using a mechanistic model of coupled components and real-time measurement, the thermal behaviour of the same system is simulated, calibrated, and validated; and (3) using a calibrated and validated simulation platform, designers can author and predict nuanced heat transfer profiles for new surface geometries, and thereby fabricate, measure, and characterize their performance.

Here we present results from a six-month study that implements this modelling approach using organic paraffin wax phase change materials (PCMs). PCMs undergo a phase transition from solid to liquid, and conversely from liquid to solid, at a designated temperature. In doing so, PCMs are capable of maintaining that temperature while absorbing or releasing large quantities of energy. In architecture, current PCM-based thermal energy storage systems seek to reduce overall building energy use, reduce peak energy loads, minimise HVAC system sizing, and improve overall thermal comfort [4 - 7].

DIGITAL MANIPULATION OF PHASE CHANGE MATERIALS

We developed a multiscale modelling and simulation platform for the prediction and manipulation of PCM behaviour in the presence of transient environmental conditions where context features, at small and large scales, are model features. Our approach uses a full-scale physical prototype (Figure 31 and 32) coupled to a high-resolution, geometrically explicit heat transfer model using sensors to provide continuous measurement of melting and solidification.

There are two key stages to this approach: The first is the development of a mechanistic model based on a defined model data schema, where data collected through the continuous measurement of physical prototypes are used as a means of verification, calibration and validation of simulated behaviour against predefined geometries. This effort is understood as constructing a model of the behaviours under scrutiny. The second stage extends the mechanistic model into a predictive model allowing performance simulation of proposed geometries and orientations. This is understood as constructing a model for supporting generative design. Within this second stage, we develop and test the efficacy of machine learning in making more refined predictions based on recent histories of observed data. This approach permits a team composed of designers, sculptors, materials engineers, and building scientists - the majority of whom have no training in heat transfer calculations - to engage in the prototyping, modelling and simulation process; feedback via calibration, verification, and validation routines to reorganize and redesign the facade system.

Figure 31
The testbed with video and weather sensors

PHYSICAL PROTOTYPE AND TEST BED

In order to study the relationship between model geometry and PCM melting behaviour, an adjustable apparatus consisting of 23 rhombic panels were fabricated, assembled, and monitored on-site in Copenhagen, Denmark for a period of six months. An accompanying digital mechanistic model was developed to form predictions of melting behaviour based on empirical data for internal calibration. This informed a later, the second set of panels.

Five variations in panel geometry were explored to test the hypothesis that local differences in the quantity of PCMs (in terms of surface area to volume ratio) and exposure to solar radiation should yield measurable differences in the local rate of melting.

To encapsulate the fluid volume of each PCM panel, a vacuum-formed thermoplastic shell was constructed, and two types of PCM were selected for study based on nominal melting points of 6°C and 10°C falling slightly above typical dry bulb temperatures experienced in Copenhagen during the initial study period. Hence, the combination of daytime solar radiation and night-time conductive heat loss would offer a high likelihood of complete cycling between solid and liquid state over a typical 24-hour period. The encapsulated PCM panels were mounted to the front face of the adjustable testbed enclosure and placed in an exterior courtyard where they remained for the duration of the experiment (Figure 32).

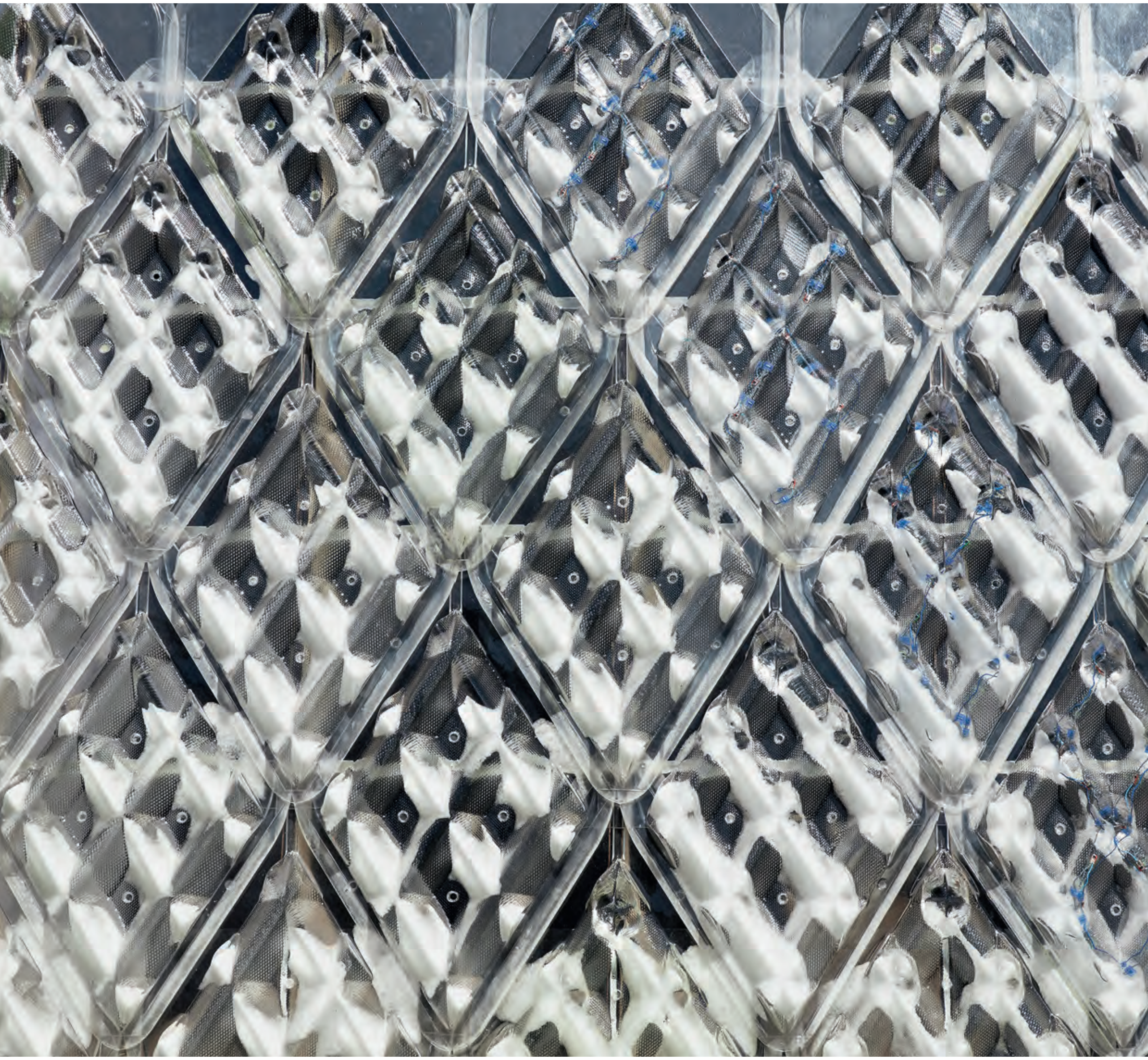


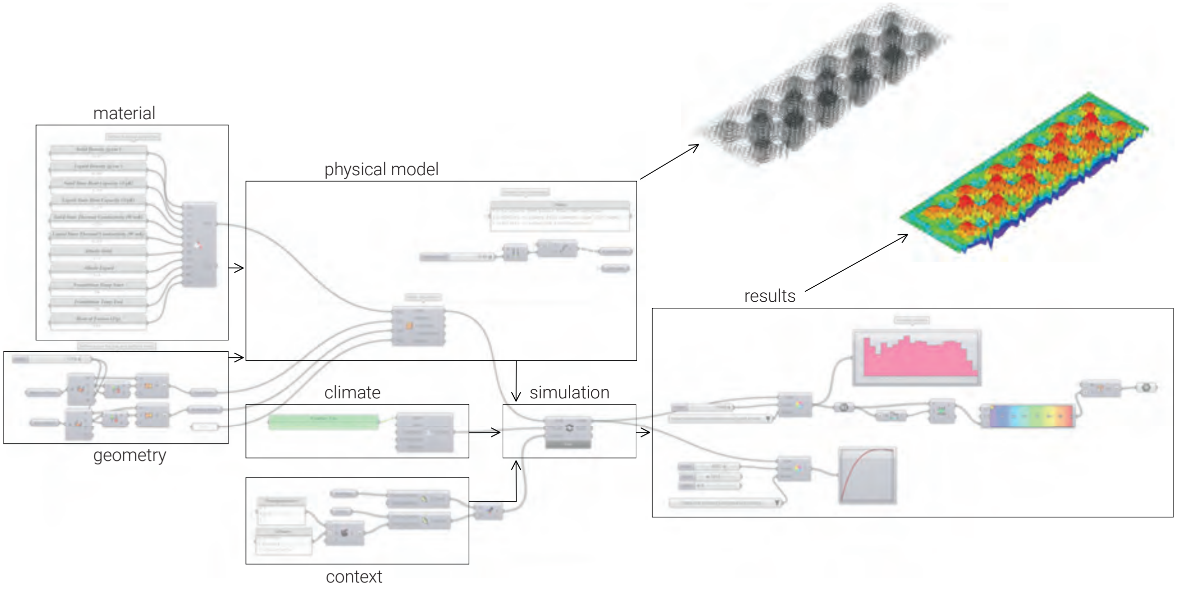
Figure 32
Array of PCM Panels on the Testbed

Wire temperature sensors were arrayed across the inside face of the PCM panels and throughout the 84 panels in order to monitor the interior environment of the apparatus and its contribution to PCM melting behaviour. The array of temperature sensors send data in 5 min intervals via Pointelist an ecosystem for wireless collection of high-density sensor data [8], to a web API for subsequent viewing and analysis. Ambient conditions at the testbed site were monitored by a local weather station, which was mounted adjacent to the testbed and gathered various relevant quantities, including dry bulb temperature, humidity, wind speed and direction, and total horizontal radiation. A time-lapse camera recorded changes in PCM state, direct sunlight, and cloud cover in five-minute intervals to coincide with temperature recordings (Figure 31).

MECHANISTIC MODEL STRUCTURE AND HIERARCHY

The modelling and simulation platform attempts to predict the behaviour of the PCM testbed under varying environmental conditions and calibrate predictions against observed behaviour. As an interactive tool, it allows exploration of various geometric forms and siting to guide design iteration; imputation of various material properties to aid in PCM selection; and use of historical or projected weather data to correlate findings with observations and make predictions about future behaviour. Based on the project goal of engaging in rapid geometry iteration, we used Grasshopper's extensible framework and developed new components to capture the simulation inputs, execution, and results in visualisation within a single design environment. These components roughly divided into six modules: Climate, Context, Sensor, Material, Geometry, Simulation, and Results (Figure 33).

Figure 33
System Overview of the mechanistic model in Grasshopper



MACHINE LEARNING PREDICTION OF MATERIAL BEHAVIOR

A multiple linear regression model of the observed behaviour was developed as a complement to the mechanistic model in order to determine near-term predictions of PCM behaviour and rankings of features that influence these predictions. The training data were drawn from the weather station recordings of outside temperature and radiation, interior sensors' temperature readings, and readings from 11 sensors embedded in a single panel. At each timestep, feature vectors were created for the complete set of readings, and prediction vectors were created for panel sensor reading, both in a range of intervals. The model was trained using the Multiple Linear Regression model of the SciKit learn python library using three days of data and subsequently used to predict running predictions over the following seven days, for which empirical data were also available. In this manner, the accuracy of the predictions could be assessed relative to recordings that were outside of the original training sets.

VERIFICATION OF RESULTS

The verification of the mechanistic model was conducted through qualitative visual inspection and quantitative numerical analysis of time-series predictions, both of which utilised the simulation interface.

For visual inspection, images of simulation steps were compared with concurrent time-lapse images of the panels in situ to confirm that the melting patterns bore a resemblance to predicted behaviour. The mechanistic model was largely successful at predicting the qualitative melting behaviour, which began where the PCM thickness was minimal and proceeded gradually to the thicker regions where more enthalpy was required to melt the material (Figure 34).

The multiple linear regression model produced accurate forecasts of system behaviour based on three days of training data. As was expected, the 5-minute forecast yielded the most accurate predictions (standard deviation for the 11 sensors between 0.15°C and 0.23°C), while the 20- and 60-minute forecasts yielded slightly larger deviations (between 0.29°C and 0.47°C and between 0.47°C and 0.76°C). What is notable about the deviations in the longer-range forecasts is that they occur largely in the liquid state, where the aforementioned solar effects complicate analysis. Conversely, these models proved extremely effective at predicting the onset and duration of melting and solidification, suggesting that they are well-suited to forecasting the visual effects of phase change, which are the primary focus of this study.

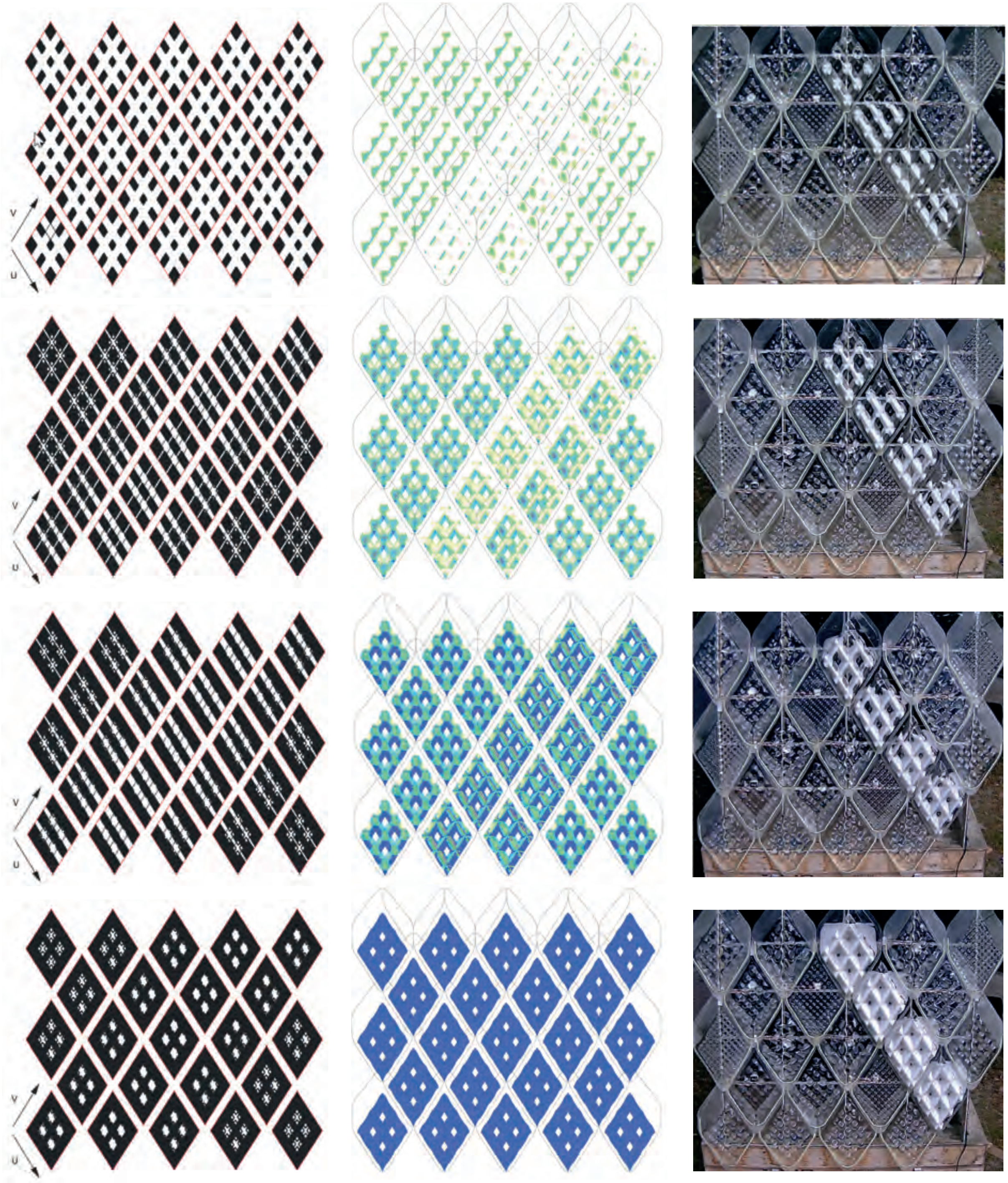


Figure 34

The designed (left), simulated (middle) and observed (right) behaviour of the phase change of an initial row of PCM panels.

In conclusion, the design-based context contrasts with approaches to PCM modelling presented in the scientific literature because it seeks to model PCMs that are exposed to a broader set of conditions than are typically encountered in controlled scientific experiments in service of informing the design and performance of an experimental architectural envelope. In contrast to much of the literature, which considers PCM's exclusively from a thermal perspective, our architectural motivations have supplemented thermal consideration with a focus on optical properties. Recent literature has focused on optical properties, with PCM used as fill between multiple layers of glass for optically switching windows, or as operable and adjustable slats and louvres [9][10], which aims toward thermal equilibrium and visual homogeneity. Our work contributes methods that support the design of heterogeneous and localised zoning of thermo-optical conditions and, critically, supports informed design and definition of model boundaries.

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Brundtland’s conception of sustainability was principally aimed at limiting damage to ecosystem(s) and human health. However, the principles of the Paris Climate Agreement and the UN Sustainable Development Goals call for a new approach that goes beyond ‘limiting damage’ by conceiving of built environments that "create a positive impact" on both the local ecosystems and on human health and well-being. In short, what is called for is regenerative design.

The principles of regenerative design require the design process to be inclusive and collaborative; architects, engineers, scientists from a range of disciplines and many other stakeholders must work together to reverse the damage that has already been done and seek to create further positive impacts to allow ecological systems to regain and maintain a healthy state. As such, regenerative designs should aim to create clean and temperate cities and buildings that stimulate human well-being and health.

The edited book offers those involved within the built environment a wide range of insights into regenerative design from international design practitioners and researchers in the field. As well as theoretical insights into the historical, cultural and philosophical development of regenerative design, practical insights are framed in a set of key regenerative design principles, methods and performance simulation tools. Finally, the ability to create regenerative designs and the positive impacts they bring are demonstrated through a series of built examples.

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