REGENERATIVE DESIGN IN DIGITAL PRACTICE

A Handbook for the Built Environment

Edited by

Emanuele Naboni
Lisanne Havinga

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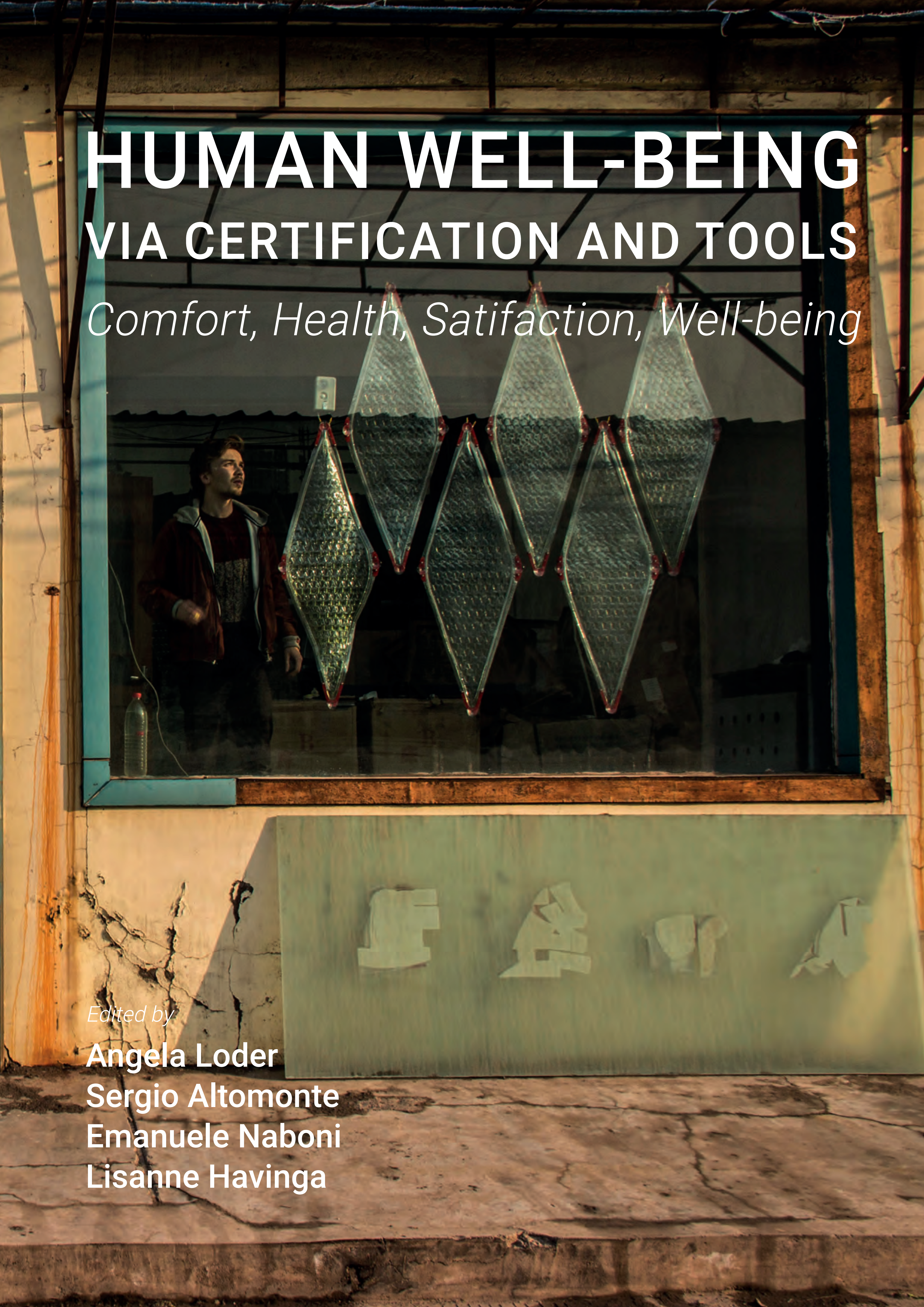
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

RESTORE
REthinking Sustainability TOwards a Regenerative Economy



HUMAN WELL-BEING
VIA CERTIFICATION AND TOOLS

Comfort, Health, Satifaction, Well-being

Edited by

Angela Loder
Sergio Altomonte
Emanuele Naboni
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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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PROMOTING HUMAN HEALTH AND WELL-BEING IN BUILDINGS

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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

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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

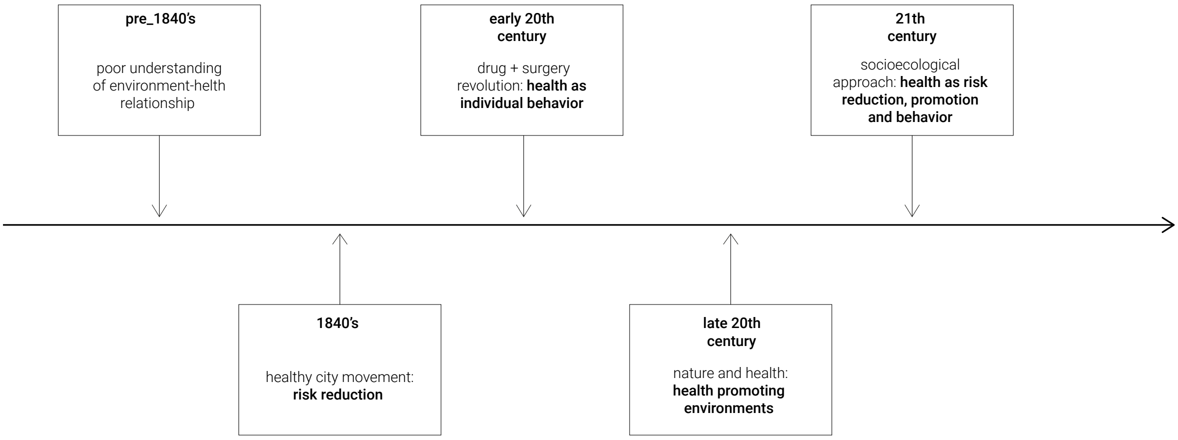
Many of the models that come from ecosystem services consider a risk reduction approach to health, *e.g.* the reduction in flooding and heat stress from better designed infrastructure [1]. Similarly, at a building level, experience from adverse health outcomes, such as sick building syndrome from energy-efficient 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.

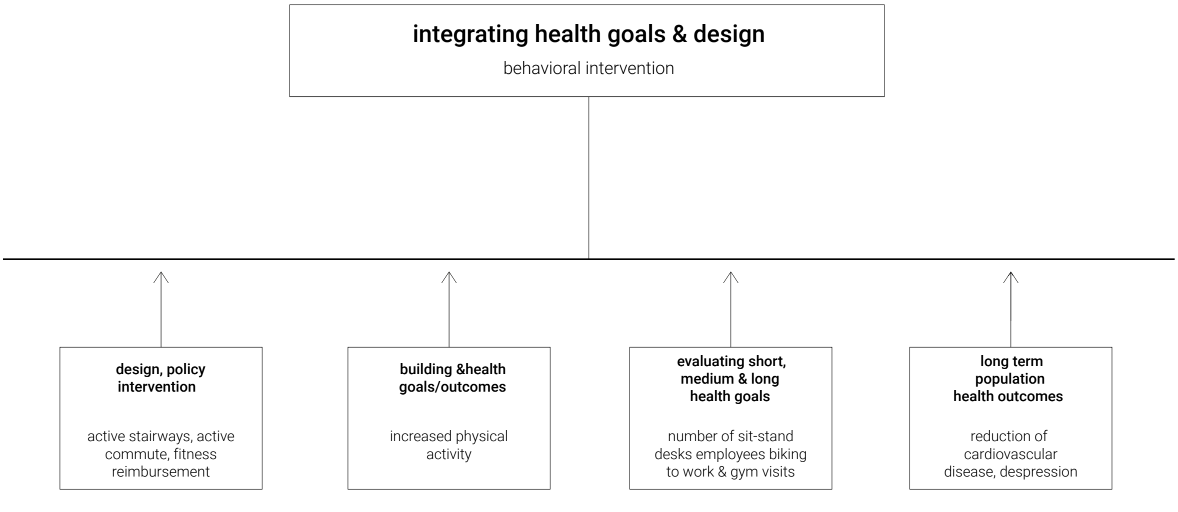


Figure 2
This image shows how designers might approach adding health goals to their project. Designers should begin with the health goals and desired outcomes, move backwards to decide which intervention will help them achieve those outcomes, and then move forwards to list different methods to evaluate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

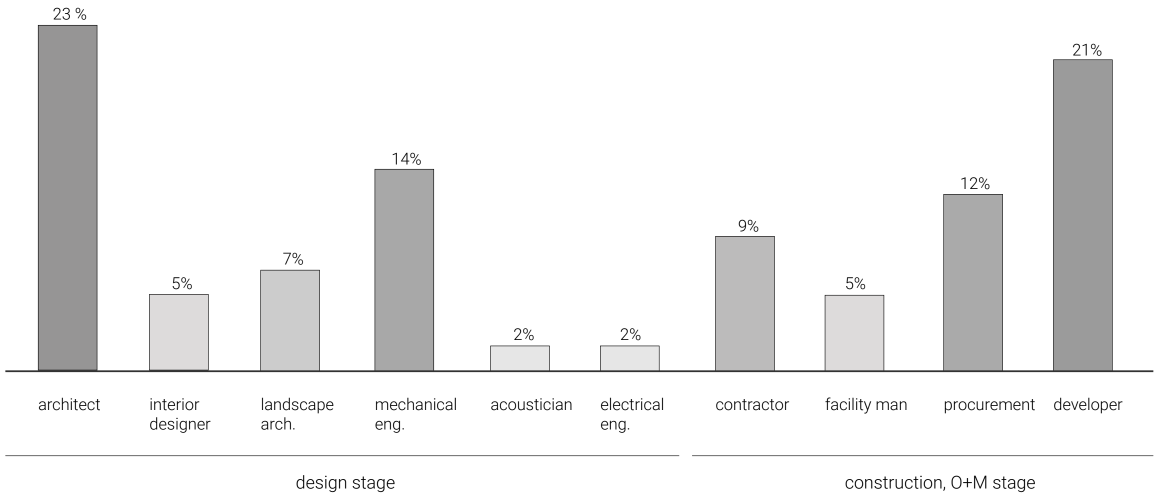

Figure 3

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).

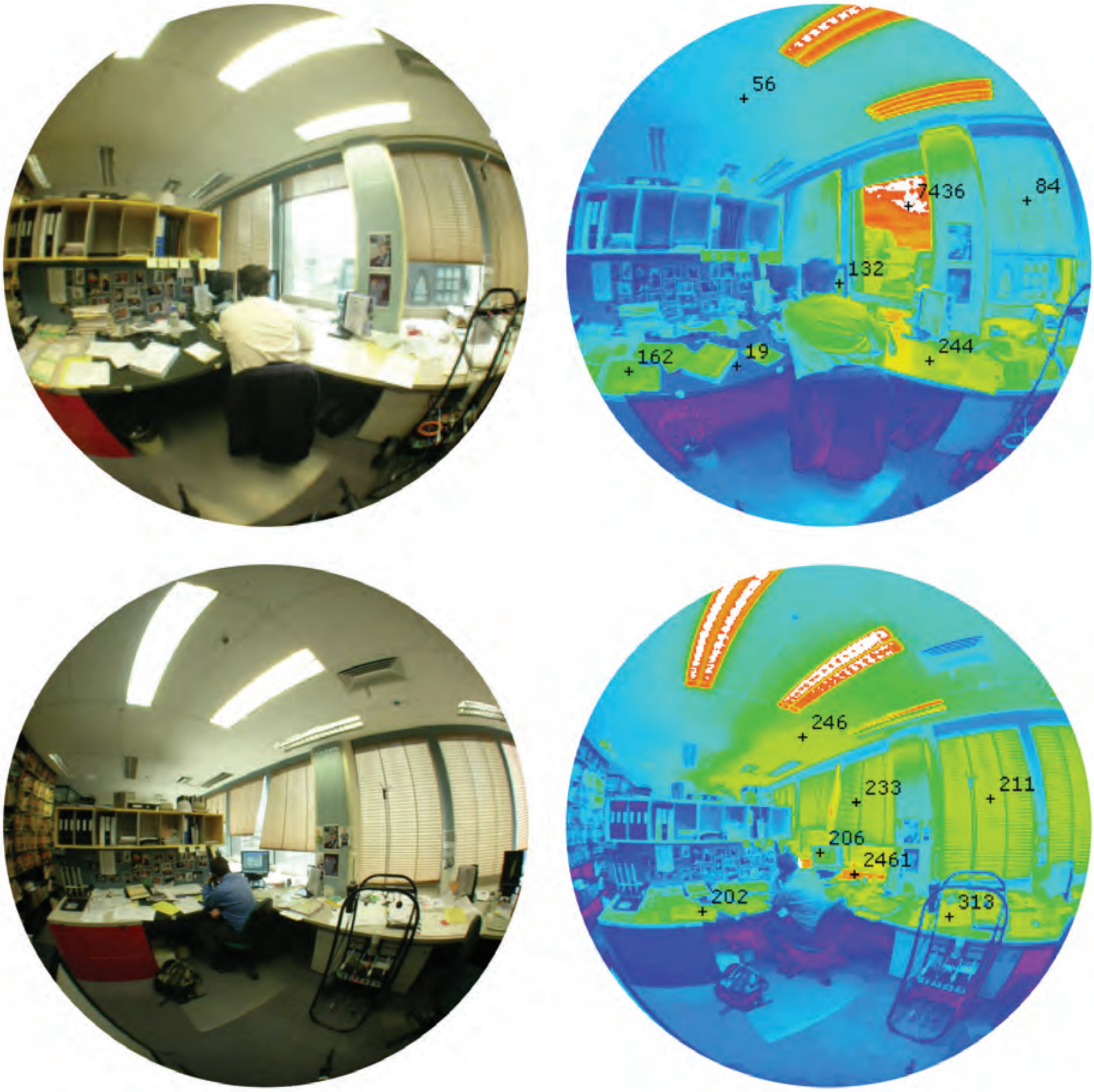

Figure 4
Fish-eye lens (left) and luminance mapping (right) of lighting conditions in an office during winter (top) and summer (bottom). Responses to the risk of discomfort due to glare show seasonal variability that might be independent from physical parameters.

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.


4
3
2
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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).

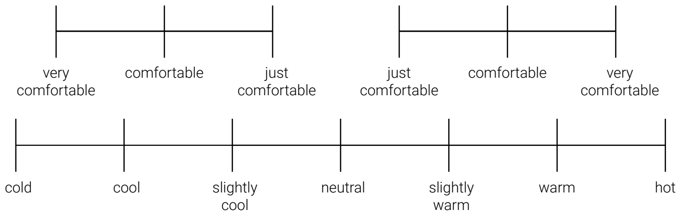


Figure 11
Visual Analogue Scales used in the questionnaires to assess thermal sensation (above) and thermal comfort (bottom). Note that the thermal comfort scale is divided into two parts to urge participants to indicate whether they perceived the thermal environment as 'comfortable' or 'uncomfortable'.

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.

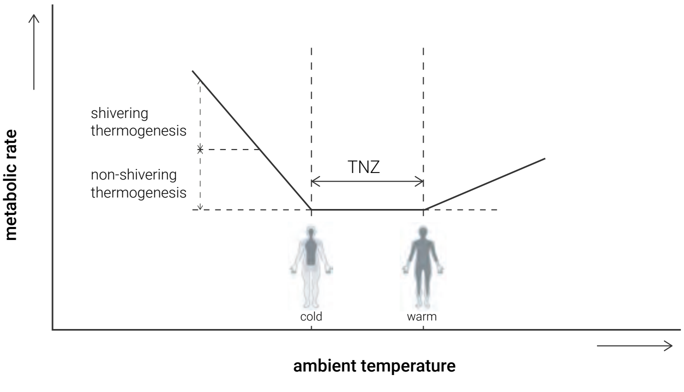
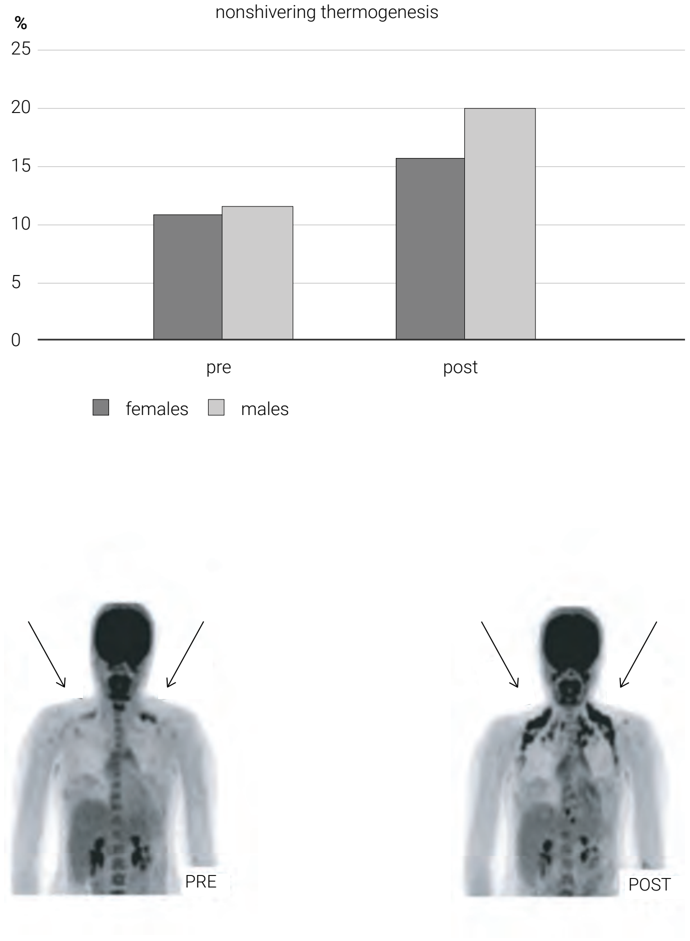


Figure 12
The physiological thermo-neutral zone (TNZ, adapted from [18]) (non-shivering thermogenesis, NST; shivering thermogenesis).

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).

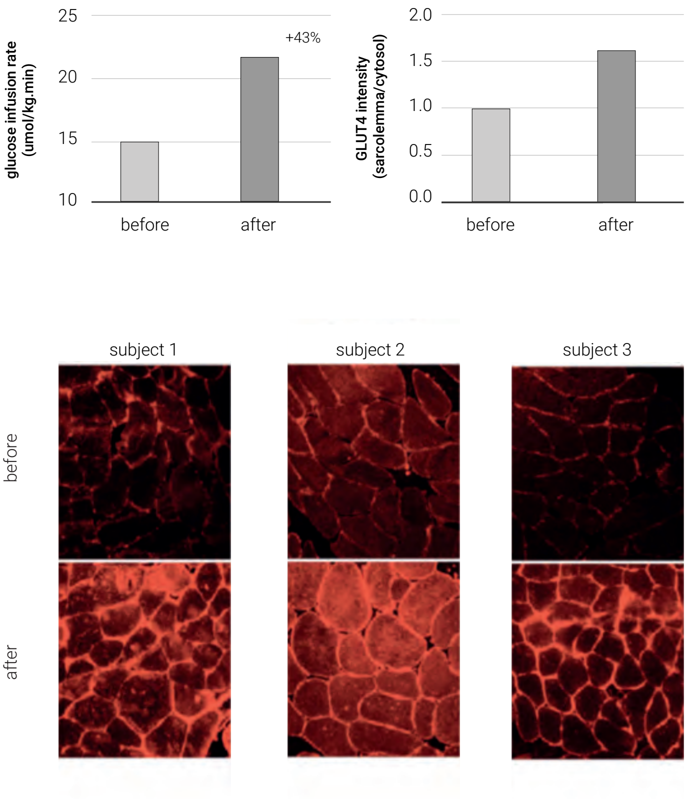


Figure 14

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.

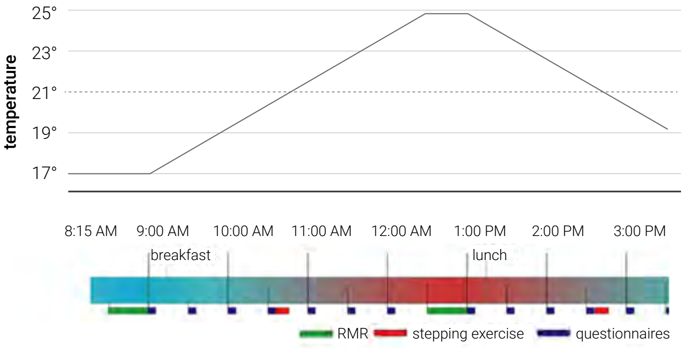


Figure 15

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.

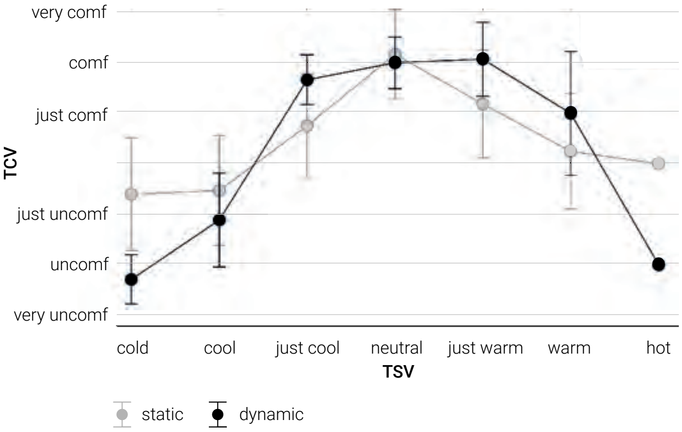


Figure 16

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].

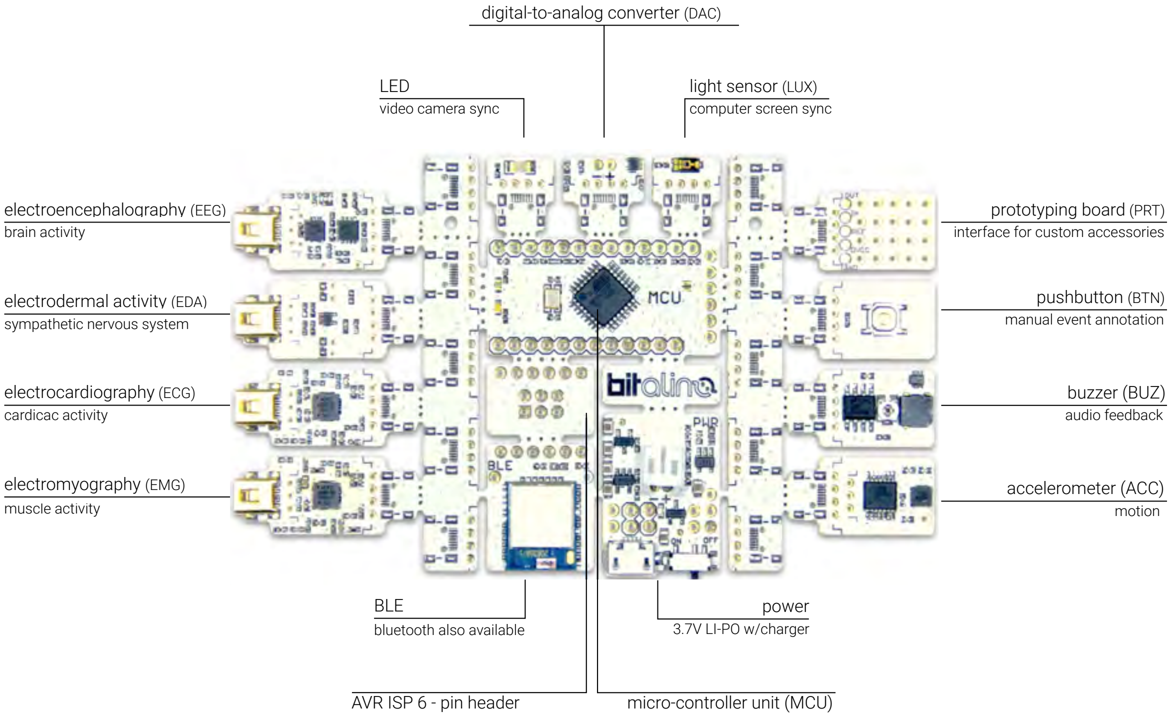
FROM THE LAB TO THE ARCHITECTURAL SPACE

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.

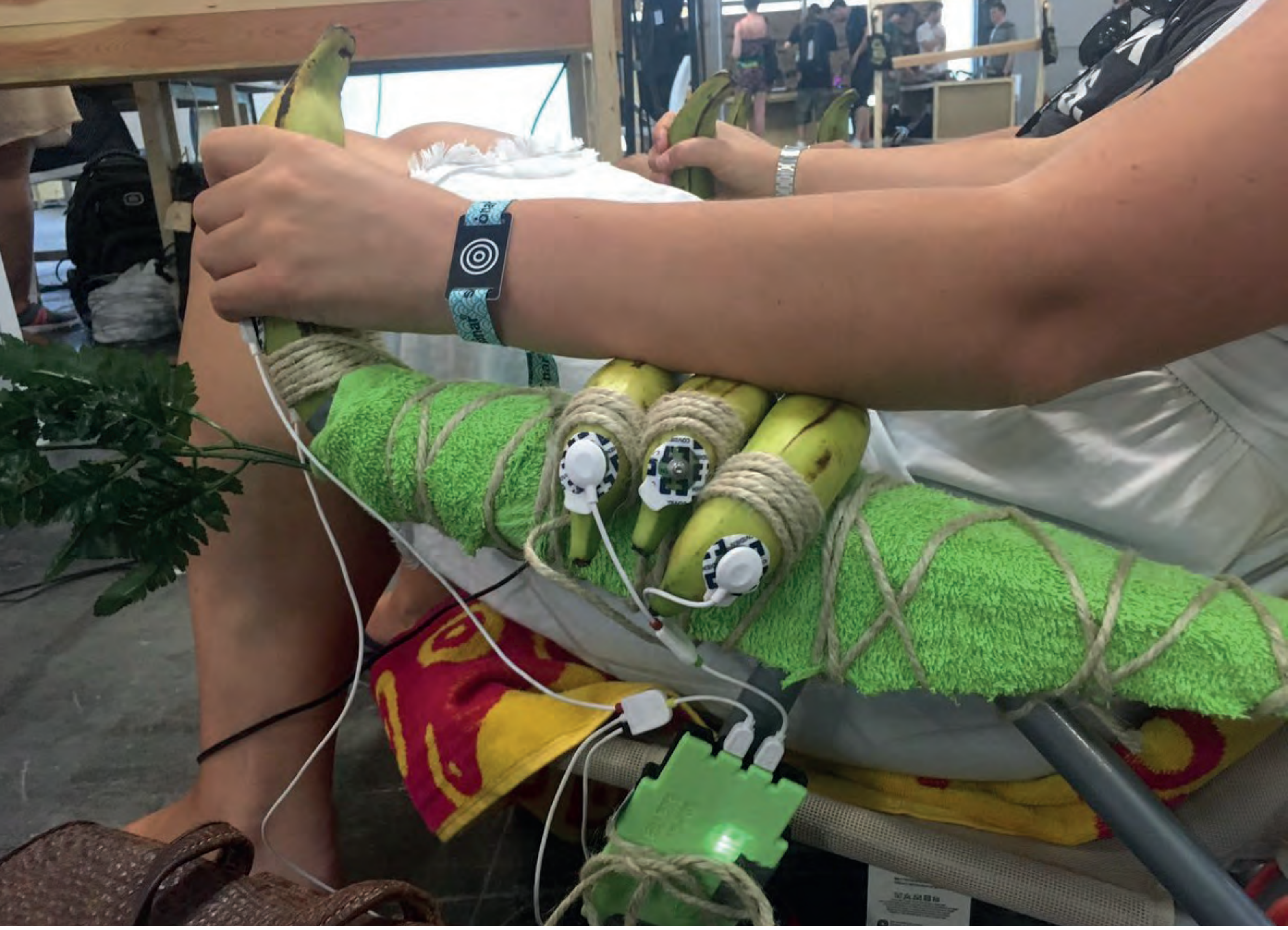


Working at the interface between wearables and architectural elements, the 'Atmospheric Delight' installation [22] produces generative feedback loops between spatial scenarios and user experiences. In this work, a building is considered as a repository of indoor microclimates and use biosignals to assess 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 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.

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.



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).

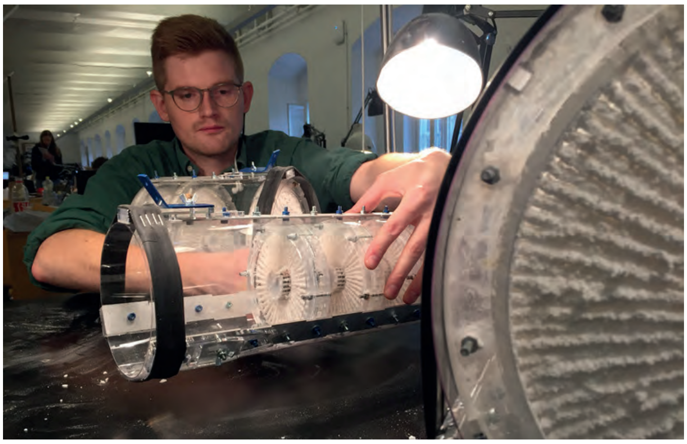
THE CONCEPT OF ARCHITECTURAL DEVICE

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)

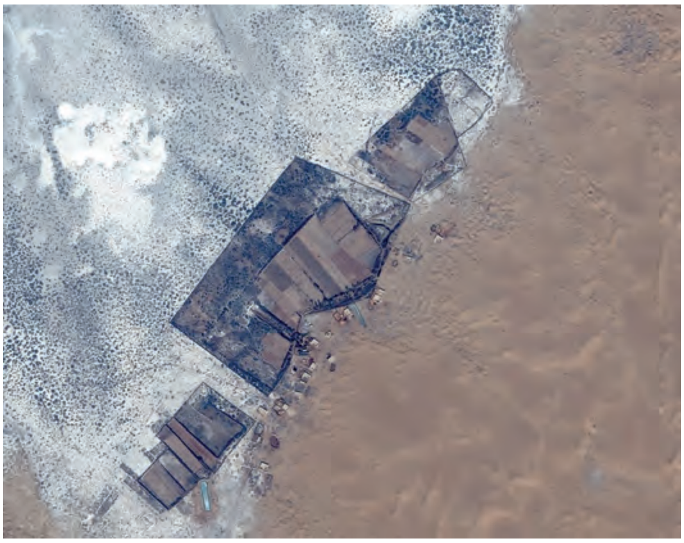


Figure 25

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.

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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