



1. INTRODUCTION— COMPUTING THE ENVIRONMENT:

DESIGN WORKFLOWS FOR THE SIMULATION OF SUSTAINABLE ARCHITECTURE

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That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives. ... There is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world.⁽¹⁾

—Carl Sagan

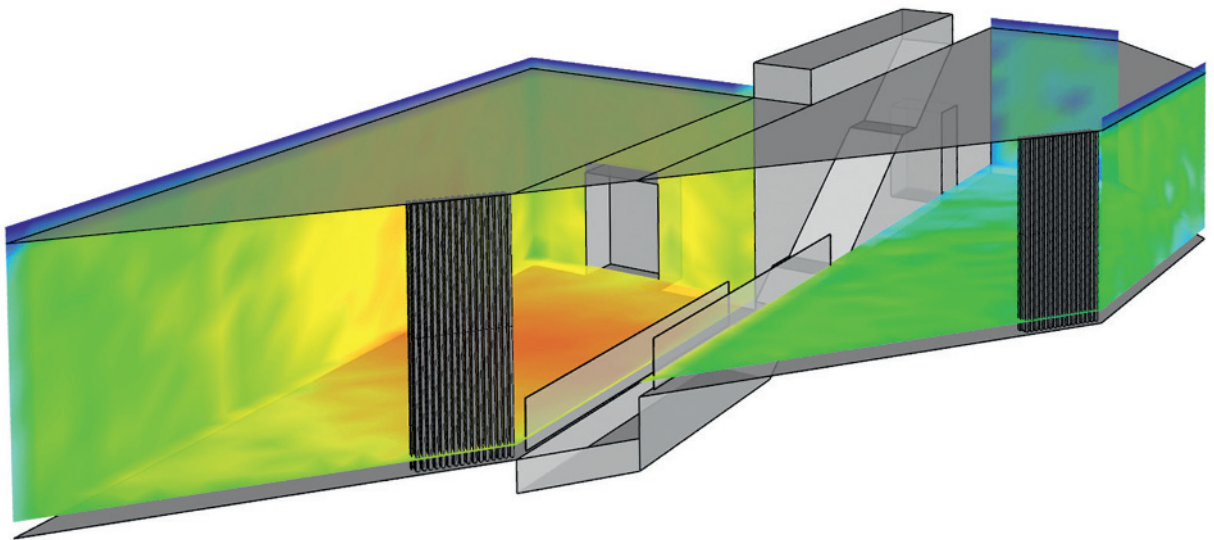
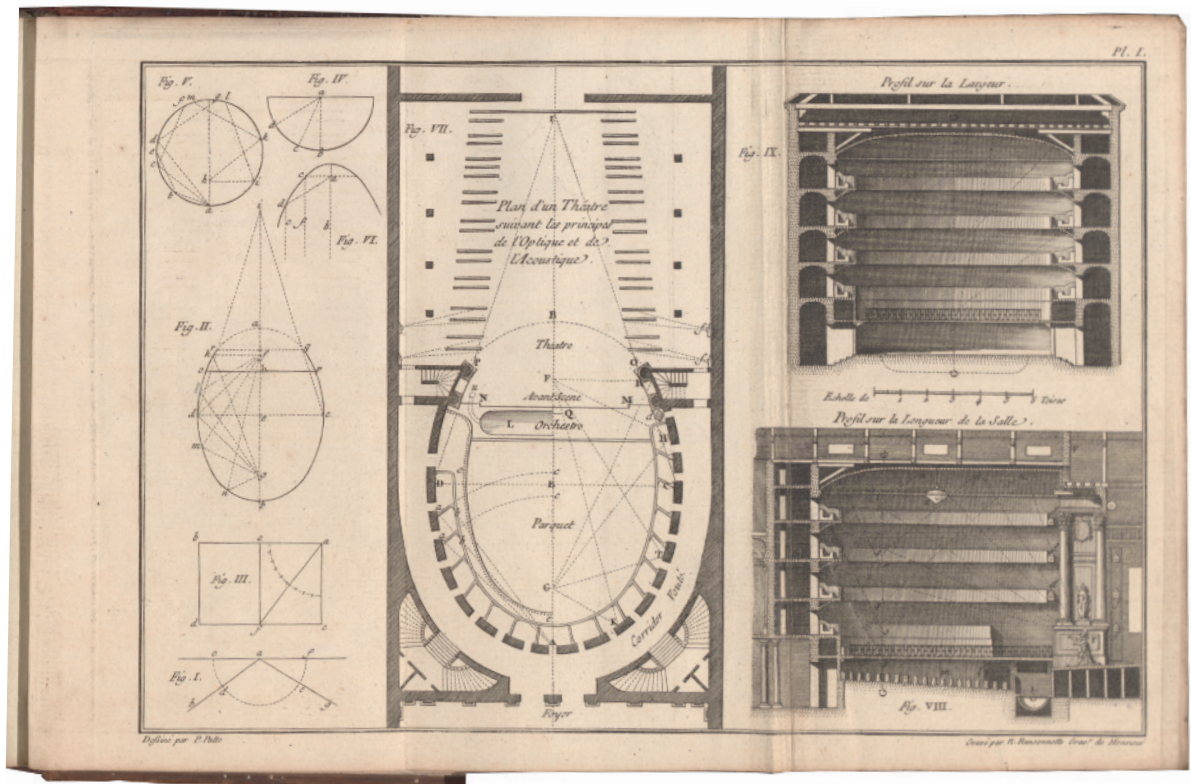
1 Earthrise image of Earth, photographed by astronaut Bill Anders during a 1968 Apollo mission, the first manned voyage to orbit the Moon

This photograph is renowned as an influential environmental image, sparking people's impression of Earth as vulnerable and small in a large expansive universe. Looking back on Earth, it seems potentially fragile, a finite, closed-loop system.

Architects design for the future. The act of drawing is a predictive act of experimenting with possible futures. The buildings architects design today form the cities of the future. Necessary optimists, architects design to achieve better ways of living—turning 'existing situations into preferred ones'.⁽²⁾ In architecture, the vast majority of projects are now designed in virtual environments; and, beyond architecture, in almost all sciences, we are seeing the rise of computer simulations as more and more experiments are carried out 'in silico'.⁽³⁾ Simulation is a way in which designs can be tested for their future performance. In architecture, 'while simulation once pertained to modes of presentation, it now connects architecture to the natural sciences and to a methodological and strategic instrument, a tool of knowledge'.⁽⁴⁾

A 'model' is an approximation of the real world, and following the building of models, simulations are repeated observations of models that enable analysis and visualisation of behaviour.⁽⁵⁾ Architects have always used simulations—tools to forecast a range of behaviours in buildings. Yanni Loukissas suggests that this way of working is not new in architecture—Filippo Brunelleschi invented linear perspective to simulate the perception of space, Pierre Patte used ray diagrams to simulate sound and Antoni Gaudí used graphic statics to simulate structural performance. While in today's practice, numerical methods have overtaken graphical techniques in the domains of visualisation, sound and structural performance, what remains constant is the notion of simulation—the desire to get feedback from the design environment.⁽⁶⁾

Like many architects, Bjarke Ingels designs by imagining a whole new world from scratch. Discussing the work of science fiction author Philip K Dick, Ingels says: 'the whole story is a narrative pursuit of the potential of the idea or innovation; he writes about



2 Pierre Patte, acoustic ray-tracing theatre design diagrams, 1782

This drawing of sound paths and their reflections off interior surfaces was used as a way of understanding acoustic performance.

This is an early example of performance analysis. Architects have always been interested in this, but digital simulation tools offer more sophisticated and precise options for computing performance, including sound, light and airflow.

3 BIG, Mexico City Villa, 2016, acoustic simulation

This simulation uses Pachyderm, developed by Arthur van der Harten, a plug-in for Rhino that is used for acoustical analysis and simulation. Simulation can be used to understand how material and geometry impact acoustical performance, and this study looks into how the main stair could work as a sound absorber.

what unfolds as a result: problems, conflicts, possibilities, freedoms ... it's almost like unleashing a whole new universe based on a single triggering idea'.⁽⁷⁾ Ingels describes his design process in a similar way: 'as soon as I discover some kind of innovation that has altered the game, making the project is like pursuing the consequence of these changes—at that point, I don't have to come up with lots of new ideas; I just have to work with the consequences of a single innovation'.

Simulation is what allows architects to 'work out the consequences' of their innovations.

DATA, DRAWING AND SIMULATION

Now these simulations are carried out using computers—and have become part of the (almost) everyday practice of architecture. Simulations transform quantitative models of building physics into qualitative sensory experiences. Internally, these simulations are purely numerical, but through visualisation (and auralisation) can create convincing sensorial events for architects and clients to consider. 'In sustainable terms, the complexity and inefficiencies of buildings present the most challenging environmental problem. Simulation remains the primary tool for the designer to develop intuitions and analysis of performance,' Azam Khan and Andrew Marsh explain. The software developers say: 'simulation is about complex relationships and time. Complexity can be defined in many ways, however, put most simply it describes a system in which unspecified emergent behaviour can be observed'.⁽⁸⁾

The digital has been accused of 'losing its materiality' and it has been said that it 'edges out the real' by the psychologist Sherry Turkle.⁽⁹⁾ However, this book can be seen as an extended argument that the use of computational design tools now enables critically important aspects of environmental performance to become part of the architectural design process; and that through computation designers can better predict what is real and measure the impacts of materials and energies. Aspects of design that were previously impossible or difficult to design for, can now be incorporated into the architectural design process.

Designers are adopting a new generation of accurate and specific simulation tools. Khan and Marsh predicted in 2011: '[the] future of simulation lies in three areas: more detailed modelling, building integration and becoming an indispensable part of any design process; that is, simulation as a design tool'⁽⁸⁾. Through the use of design simulation, building performance can be predicted. Early geometries can be compared for energy use, daylight, shading, airflow, comfort, sunlight and other parameters. Kjell Anderson writes: 'simulations provide immediate feedback about the consequences of design decisions, continued use of simulation software validates and hones an individual's intuition'.⁽¹⁰⁾ He further explains that simulation itself can be a highly creative act, it helps designers develop intuitions on real performance, as 'play leads to understanding'.

COMPUTATION IN PRACTICE

The contemporary concepts and workflows in *Computing the Environment* have roots in earlier design experiments and technological advancements, and a path can be traced from early parametric modelling to current advances in custom tool development. In 1963, Ivan Sutherland created the first computer program to design architecture. He created a program that could not only draw geometry, but also create relationships between different elements in the design (associative modelling), and compute basic structural performance analysis.⁽¹¹⁾ However, when design software was introduced to architectural practice, it only functioned as a virtual drafting board; the important 'computed' aspects of parametric relationships and performance were not included. Starting in the early 1980s, 2D drafting continued the practice of representing buildings as multiple 2D drawings. 2D drafting technology could be retrofitted to existing design practice, using existing skills without challenging established professional methods and conventions.⁽¹²⁾

Robert Aish sees the history of computer-aided design (CAD) as being divided into three eras: the 2D drafting era, the building information modelling (BIM) era and the design computation era. The BIM era actually started before the 2D drafting era in the 1980s, and is based on the idea that buildings are assemblies of components, but that does not necessarily imply that a designer conceives of a building in terms of such assemblies. This 'component' assumption forces the designer to think about micro ideas (the components) before macro ideas (the building form). The design computation era introduced the distinction between a generative description of a building and the resulting generated model, and introduced a process where the designer no longer directly models the building, but instead develops an algorithm whose execution generates the model. There are two ways in which this enables a completely different kind of architecture to be created: first, it enables a move away from manual modelling and encourages the adoption of generative design tools; and second, it allows the designer to create his or her own components and, more importantly, to define a building and its components in terms of its behaviour.⁽¹²⁾

A DEEPER WAY TO THINK

In the late 1990s, in response to the lack of functionality in available programs, a few architects began to borrow technology from other industries: physics engines in game software, and parametric and fabrication abilities in industrial and aerospace software. Perhaps now we are beginning to re-establish the vision of the original innovators (such as Sutherland), that CAD is not a better way to draw, 'but a deeper way to think'.⁽¹²⁾ Designers are 'moving away from employing computational design as a means to produce conventional architectural representations towards something more', according to Volker Mueller and Makai Smith. They are searching for ways in which to expand the scope of what may be represented computationally: material properties, energy flows and other informational aspects.⁽¹³⁾ People movement, solar

performance, daylight and glare, acoustic performance, airflow, thermal comfort and energy use can now be accurately simulated. The barrier to entry has been lowered to such an extent that all practitioners and students can now use advanced tools. Simulation software, which was only decades ago the domain of specialists and highly expensive, is now freely available on the internet and fully customisable to project demands. It appears that it is architects' new ability to 'compute the environment' that will reconnect the architectural design process with 'real-world' performance issues. This is largely to do with the widespread popularity of Rhino and Grasshopper. Using an 'open innovation' concept, Robert McNeel enables people to create their own 'plug-in' design software, and this has spawned a whole 'ecosystem' of new and innovative computational design tools for architects. Architects are increasingly the authors of their own design environment.⁽¹⁴⁾

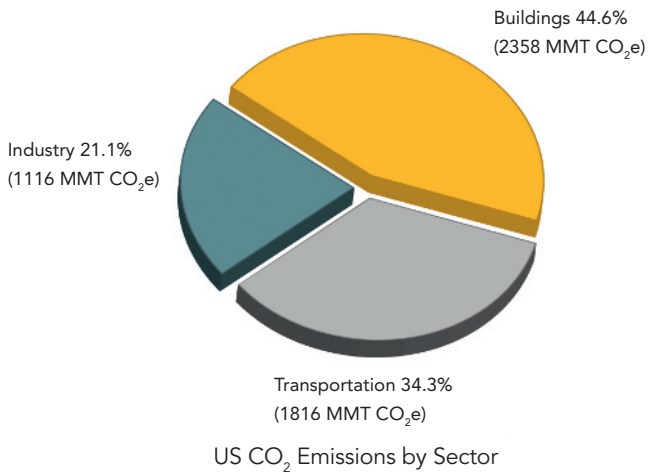
ENVIRONMENTAL IMPACTS AND THE HUMAN DIMENSION

We lack even basic things like data calculation methods and basic knowledge about sustainable building design. ... We have no methods for the design and construction of truly recyclable buildings. ... The list of missing knowledge is long.

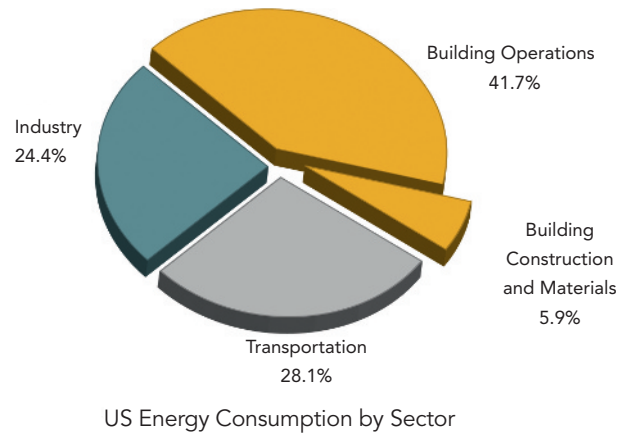
—Werner Sobek⁽¹⁵⁾

Human actions are changing our climate. Climate change and extreme weather events are having an undeniable impact on our built environment, with new regulations, mindsets and timeframes for sustainable design and development emerging from multiple sectors. The building industry uses a tremendous amount of energy, creates pollution, material use. The construction, operation, maintenance and demolition of buildings have an enormous impact on the environment and our shared resources. Renewable energy, passive environmental design strategies, low-energy techniques, life-cycle assessment, and integrated neighbourhood and community designs will become increasingly important topics for simulation and digital design. Computational design tools and workflows are a wide topic area, and we chose to focus on those particularly relevant to environmental design, such as energy use, daylighting, life cycle, thermal comfort and other design topics, rather than structural design or other parameters. There is a need for more research into how digital tools can advance sustainable architecture.

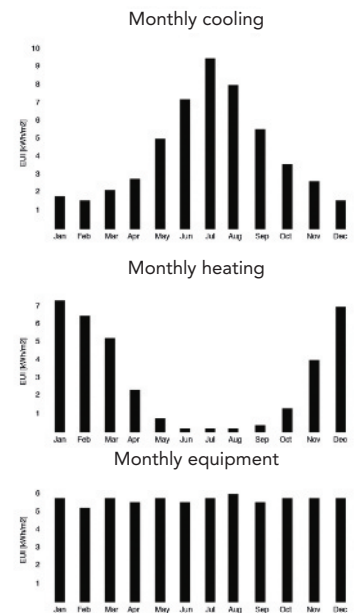
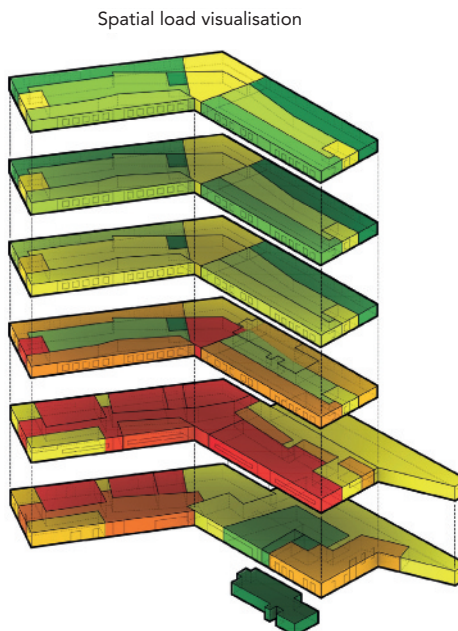
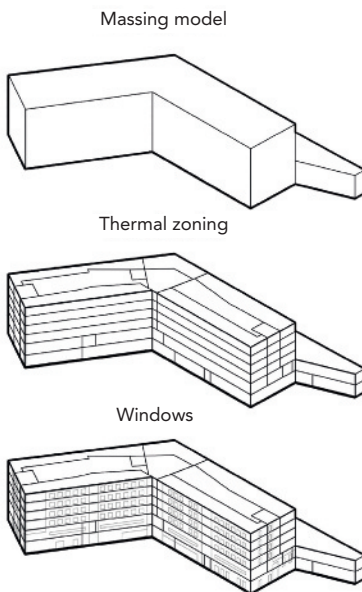
There are areas of tremendous potential for architects to positively affect humans' impact on the environment. Architects must synthesise broader societal concerns of climate change, energy and resource use together with the site specific and local environments of architecture. There now exists, with computational design tools, the ability to design better performing buildings using more accurate simulation tools. New functionality in industry standard tools such as Revit is making it easier for architects to design for and manage environmental parameters. For



4 United States CO₂ emissions by sector, 2012
Buildings are a significant source of emissions and the 2030 Challenge is a global architecture and building industry initiative that aims to incrementally lower building-related emissions and energy use by 2030, so that they use no fossil fuels and greenhouse gas-emitting energy to operate.



5 United States energy consumption by sector, 2012
To make the largest impacts on energy consumption in buildings, the focus should be on building operations. The 2030 Challenge seeks to transfer the building industry's focus on fossil fuels to renewable energy sources.



example, the Insight 360 tool includes an automated workflow for understanding photovoltaic energy production and the impacts on building costs. The tool creates a graphic dashboard for the design of renewable energy sources, so users can adjust settings such as panel type, percentage of roof coverage and payback period, and then see the impacts of these decisions in the Energy Cost Range of the model. Another example is the Tally tool, which runs within the Revit BIM design environment. It was developed by KieranTimberlake, which offers a life-cycle analysis tool to quantify embodied energy along with other environmental impacts and emissions to land, air and water.

The book relates to leading green rating systems, including Leadership in Energy and Environmental Design (LEED), and the principles of the 2030 Challenge pertaining to lowering building emissions, focusing on how new digital simulation and modelling tools are integrating with these systems. However, there are aspects to building that are not so easy to predict, and those aspects have to do with buildings' interaction with people, and with the environment, over time.

Architects can compute the environment in terms of material use, energy consumption and carbon footprint but also relating to the intimate experienced qualities of light, heat, sound or airflow. The exploration of all of these invisible terrains offers new potentials for the definition of architectural space, enclosure and meaning in architecture. Beyond the critical importance of designing buildings that are sympathetic to the ecosystems in which they operate, these are also fundamental aspects of health and wellbeing. Not only are these aspects of architecture important physically, but also perceptually and spatially.⁽¹⁶⁾ Sean Lally argues for an 'architecture of energies' that is much more than the building of an object on a site: 'it is a reinvention of the site itself. The microclimates of internal heating and cooling, outdoor shadows and artificial lighting, vegetation, the importation of building materials, and the new activities that will occur there create new places in time on site'.⁽¹⁷⁾ Aspects of design that were previously impossible or difficult to design for, microclimates, gradients of experience, responsive controls, can now be incorporated into the architectural design process using new computational tools.⁽¹⁸⁾

THE STRUCTURE OF THE BOOK

In contemporary practice, there are now designers who specialise in sustainability. It has been observed that often these specialist designers are situated in research and development groups, and that these individuals and groups, have tended to specialise in technology and the use and development of digital design tools and simulations as primary methods for research.⁽¹⁹⁾ There is a need for a more in-depth discussion of the inner workings and workflows of how architects are 'computing the environment' and how they define the environment, and how they use computation and digital design workflows. Instead of profiling buildings, we have profiled practices, documenting how designers work, and how they engage with computation and environmental design. This

6 Architectural energy calculation using Archsim

Archsim was developed by Timur Dogan as an energy simulation plug-in for Grasshopper and has now become a part of DIVA 4.0. Archsim links the EnergyPlus simulation engine with a powerful parametric design and CAD modelling environment.

book offers a new generation of architects and designers a sense of direction in how to contextualise their work and see a history of ideas, how to meaningfully apply the framework and concern of architecture within sustainable design practice. It is about architectural design, in particular computational methods and tools for sustainable design.

The book is structured into three sections: themed theoretical chapters, practice profiles and a concluding chapter on the future outlook. Following this introduction, five chapters outline key concepts in environmental design and focus on the associated computational design tools and workflows. These chapters begin with the large scale: we discuss issues of climate and energy, and the tools and workflows that are impacting global and local contexts; then explore the siting, massing and exterior envelope of buildings; move into an investigation of designing for the interior environment and how simulations can improve design for human comfort; and finally look at workflows and processes for life cycle and materials and at various measurement methods for quantifying sustainability. A chapter on smaller scale 1:1 prototypes and pavilions follows, which allows us to showcase more experimental approaches that are not yet found in mainstream practice, to reveal near future directions in the field.

The practice profiles are the second major section of the book. We selected a range of larger design-led offices that see their designs realised in built works. We initially intended to feature a series of exemplary singular buildings by these offices, but quickly realised that few built projects incorporate enough computation of environmental parameters and that the real story is in the design of workflows relating to computation and environmental design. We interviewed researchers and computational design specialists at eight architecture offices: Foster + Partners (UK), BIG (Denmark), KieranTimberlake (USA), 3XN (Denmark), White (Sweden), Thornton Thomasetti (USA), Zaha Hadid Architects (UK) and Woods Bagot (Australia) with a particular focus on how they integrated feedback from simulation and computational tools at early stages of the design process. We profiled engineers BuroHappold (UK), Max Fordham (UK) and Transsolar (Germany), and computational designers at the real estate company WeWork (USA) to gain an understanding of data and simulation in the design process and how this contributes to the design concept.

The final chapter is based on a series of interviews with some of the most prominent, influential and creative sustainable design theorists and educators in the world. These six are conceptually advancing the field through their thought leadership, authoring the most architecturally relevant books and papers relevant to themes in this book: Timur Dogan (Cornell University and lead developer of Archsim Energy Modeling, UMI and Urban Daylight simulation software), Werner Sobek (founder of the engineering practice Werner Sobek), William W Braham (University of Pennsylvania), Kiel Moe (Harvard Graduate School of Design), Neil Katz (Skidmore, Owings & Merrill) and Mostapha

8 BIG, solar analysis of Kistefos Museum bridge, Norway

Early design stage simulations done in Honeybee of Annual Radiation (kWh/m²), Daylight Factor (%) and Illuminance (LUX) to determine how much of the facade would be open, if the facade would need external shading and if the twist would allow for a skylight as it goes from vertical to horizontal.



9 Weathers, proposal for a new energy landscape

Sean Lally explores a speculative series of designs for what he calls 'new energy landscapes'. He argues that energy is 'more than what fills the interior of a building or reflects off its outer walls. Instead, energy becomes its own enterprise for design innovation: it becomes the architecture itself'.

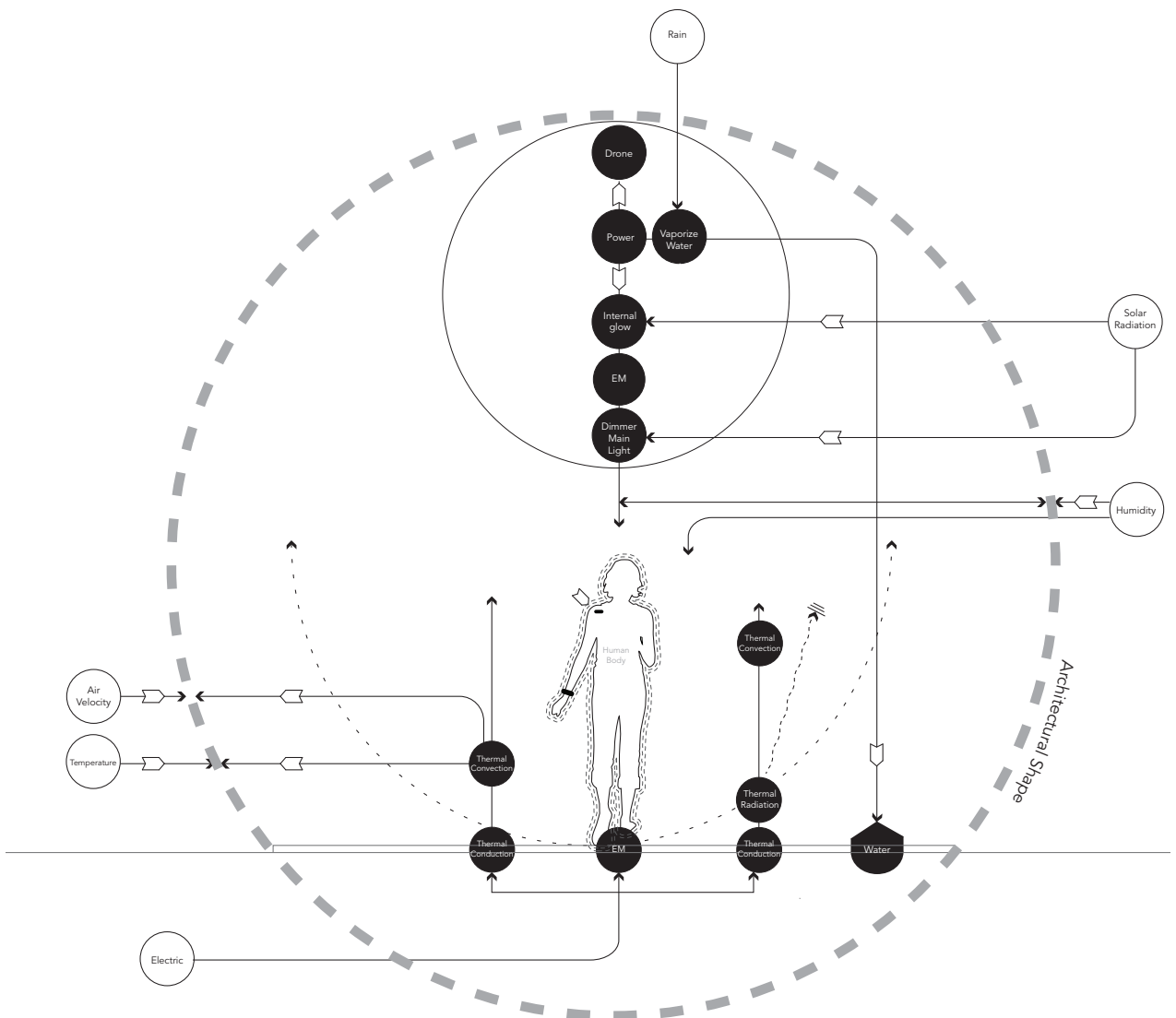
10 Sean Lally, energy shape diagram

Sean Lally of Weathers argues that architecture in the future will be the design of energies and microclimates.

Sadeghipour Roudsari (University of Pennsylvania and creator of Ladybug and Honeybee). Their expertise and critical abilities to imagine new universes for sustainable design help to situate this book beyond current practice, to begin to imagine, design and influence architecture of the future. We hope that readers will gain a critical overview of important environmental parameters and tools, learn key references and gain a further understanding of the state of the art in practice, and find inspiration to develop their own tools and workflows.

NEW POTENTIALS FOR ARCHITECTURE

Computation is redefining the practice of architecture. It can amplify a designer's ability to: simultaneously consider multiple options; connect to vast databases; analyse designs in relation to many performance parameters; create their own design tools;



and, through digital fabrication and robotic assembly, engage in the processes of building construction. Architectural practice is defined by the tools we use; as Jonathan Hill writes: 'the [modern] architect and the architectural drawing are twins ... they are representative of the same idea ... that architecture results not from the accumulated knowledge of a team of anonymous craftsmen but from the individual artistic creation of an architect in command of drawing who conceives a building as a whole at a remove from construction'.⁽²⁰⁾ So, if the practice of architecture involves the imagining and predicting of future scenarios relating to the built environment, then by probing the boundaries of new computational and simulation techniques, new potentials for architecture can be discovered, and new scenarios for how life will be in the future can be predicted.

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IMAGES

1, NASA/Bill Anders; 2, courtesy Swiss Federal Institute of Technology Zurich; 3, BIG – Bjarke Ingels Group; 4 and 5, Architecture 2030 (2013), US Energy Information Administration (2012) 2030 Challenge; 6, courtesy Manos Saratsis and Timur Dogan; 7, Ladybug, Mostapha Sadeghipour Roudsari; 8, BIG – Bjarke Ingels Group; 9 and 10, courtesy Sean Lally