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Chapter 1 | Environmental models

Wind Grid

It was early autumn the first time I visited 82251 Limekiln Line, in rural Ontario, Canada. Tall, empty husks of cattle corn marched in rows up and down the gentle topography of the 25-acre agricultural lot. Gaps between rows invited occupation. Encountering this site of a future project that first time involved experiencing it as a series of walked lines bound by walls of papery husks rustling in the wind. In contrast to the dense, urban, wind-shadowed world of Toronto where I was living at the time, on Limekiln Line wind was vivid and experiential.

Wind was also instrumental on Limekiln Line. The site was off-grid and wind offered a viable renewable energy source, although it was abandoned later in favour of solar. Wind was a powerful mediator of wide Canadian seasonal swings, tempering the heat of harsh summer sun, or, when deflected, offering respite from the bite of a winter snowstorm.

More than anything, wind was capricious. While I experienced wind at certain moments as particular points along walked lines, wind at the scale of the site was ungraspable. I wanted to better see how the wind shifted across the landscape as a continuous, moving, shape-shifting phenomenon. I wanted to understand wind and its material properties. How does it behave? What does it *look* like?

In response, I completed a full-scale site installation, *Wind Grid*, to better understand global air movement across the undulating site. With the help of family and friends, I installed over one-hundred steel poles, slotted into conduit sleeves impacted into the ground, over a 25-metre grid across the entire site (Figure 1.1). A surveyor's level established parallel and perpendicular lines. When enough poles were installed with instrumental precision, the eye fine-tuned placement between previously installed poles. This visual acuity served us well later because we had to remove the poles and reinstall them several times over the course of the installation to permit harvesting. The poles were topped with freely rotating windsocks to register air movement through the site.

When the windsocks were outfitted for the first time, I stood back, watched and remained confused. Some windsocks flapped listlessly next to others that were fully activated. It was not clear whether this was because wind was not present at that point or due to constructional defects in either the windsocks or their receiving elements. But there was a bigger issue: dips in the topography occluded vast areas of the site. Despite the three-metre height

1.1

1.1 Photograph of *Wind Grid*, a site installation on a rural property in Huron County, Ontario. Over one-hundred steel poles, slotted into conduit sleeves impacted into the ground, were installed on a 25-metre grid across the entire site. A surveyor's level established parallel and perpendicular lines. When enough poles were installed, the remainder were placed through visual perspectival alignment with previously installed poles.

of the poles, it was impossible to attain a synoptic view of wind patterns.

To gain a synoptic view of the site in this pre-drone era, I attached a camera to a makeshift harness attached to a bundle of helium balloons. The balloons buoyed the mechanical eye of the camera to a vantage point I wanted to hold (Figure 1.2). It took photographs and videos of the site as activated by the wind, promising this synoptic, site-specific view of wind movement at that moment in time. This approach, too, failed, for when the wind activated the socks, it activated the balloons as well, tossing them about, creating blurred, incoherent photographs. Wind was captured in the photograph as a moving blur, not as the clear vectors of movement I had hoped for.

I changed vantage point again, moving to the ground. The grid of steel poles offered valuable insights about other related features of the site. They served as station points for multiple topographies: the rise and fall of the earth, the inconsistent growth of crops, and the banks and drifts of snow, which varied due to the vagaries of wind and the obstacles that shadowed it. I recorded these measures as a series of annotated grid drawings (Figure 1.3). They began as messy records but gained refinement over time. Drawings increasingly prioritised the quantitative over the material, spatial and experiential. Further drawings, reminiscent of Eva Hesse's *Circles and Grids*, integrated ink washes, using one fluid medium to represent another, attempting to regain material qualities lost to the quantitative (Figure 1.4). As a body of work, the drawings fixed air movement and its indices in the landscape at discrete moments in time. Static and fragmented, they failed to capture wind as a moving fluid condition.

I eventually designed and oversaw construction of a house on the site, and then moved from Canada to Scotland during construction (Figure 1.5). The site was no longer readily accessible, but questions raised by the installation and the survey drawings persisted. Bound on two sides by forests that sped up and channelled air movement, the site was analogous to a full-scale wind tunnel. Given my distance from the site, perhaps a real wind tunnel might make global airflow patterns through the site legible at scale (Figure 1.6)? The questions of how physical models in experimental environmental chambers might reveal insights about airflow and how these insights might inform the design process initiated this book.

1.2

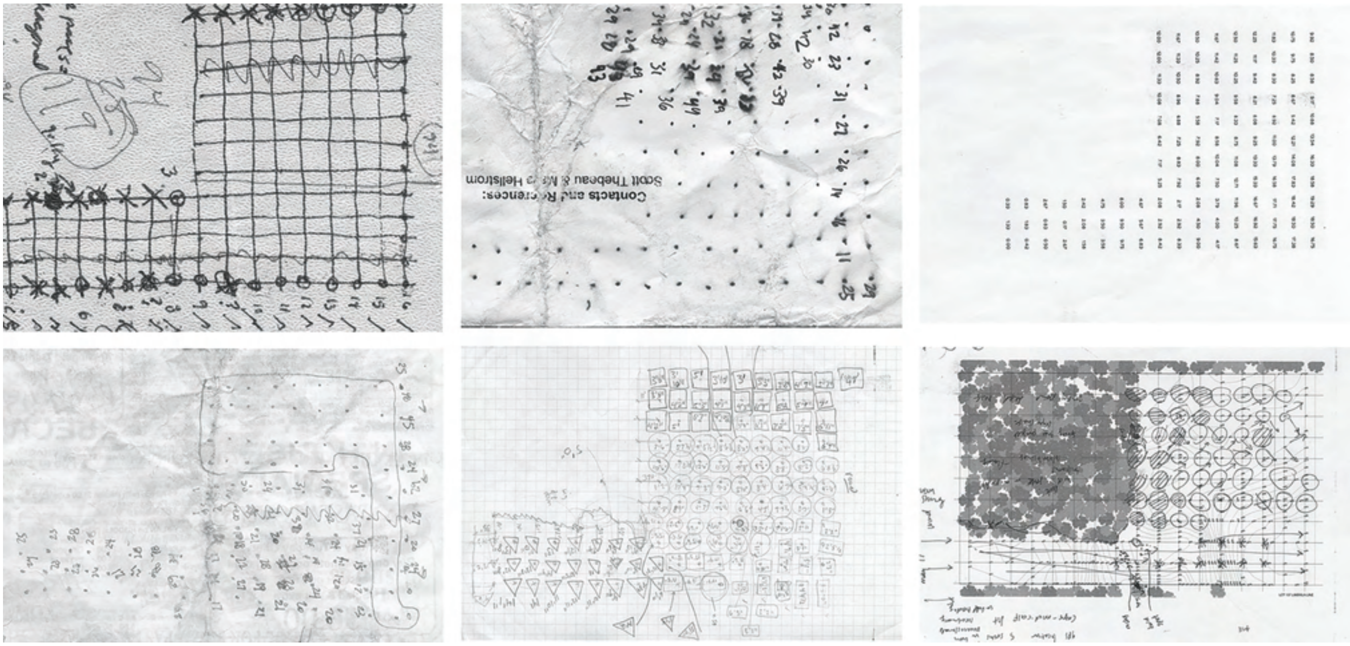
1.2 Photograph of *Wind Grid* taken from a makeshift helium balloon rig. The balloons buoyed the mechanical eye of a camera to a vantage point otherwise unattainable. When the wind activated the socks, it activated the balloons as well, tossing them about, creating blurred, shifty photographs. Wind was captured in most photographs as a blur – a reminder that recording that which is fluid and shifting requires a stable substrate.

Architectural theorist Christopher Hight refers to environmental conditions such as airflow and thermal exchange as 'non-visual phenomena object(s)' (2009, 26). As a 'non-visual phenomena object', wind is complex and resistant to representation because it is invisible, and it follows fluid dynamic principles that are not always intuitive. Solar trajectories for any given latitude are visible, legible over time and entirely predictable. Wind patterns, on the other hand, are invisible and often shift in intensity and direction erratically and rapidly.

The two predominant techniques architects use for describing air movement are static environmental diagrams, overlaying arrows of anticipated air movement, or more complex building performance simulations such as computational fluid dynamics (CFD). Many of the challenges and limitations associated with both techniques are explored throughout this book, particularly in Chapters 3 and 5. In brief, static diagrams are just that – static – representing a single moment in time and space. Moreover, they are hypothetical, failing to reveal substantive properties of air movement in the process of constructing the drawing. Building performance simulations such as CFD are unwieldy, particularly in the early design stages of a project. They are also easily misappropriated or misinterpreted by initiates. Fundamentally, neither technique captures wind as a graspable, experiential, moving material in the way that was so palpable when walking through the rows of papery stalks that first time on Limekiln Line.

This book presents a third technique, using physical models incorporating moving air and water, referred to as *environmental models*, for making the 'non-visual phenomena object' of airflow materially tangible. This approach is based neither on rules-of-thumb nor on complex digital simulations. It is based on observation, on tight-tolerance fabrication and on direct engagement with fluid materials, appealing to the architect's inherent spatial and material sensibilities.

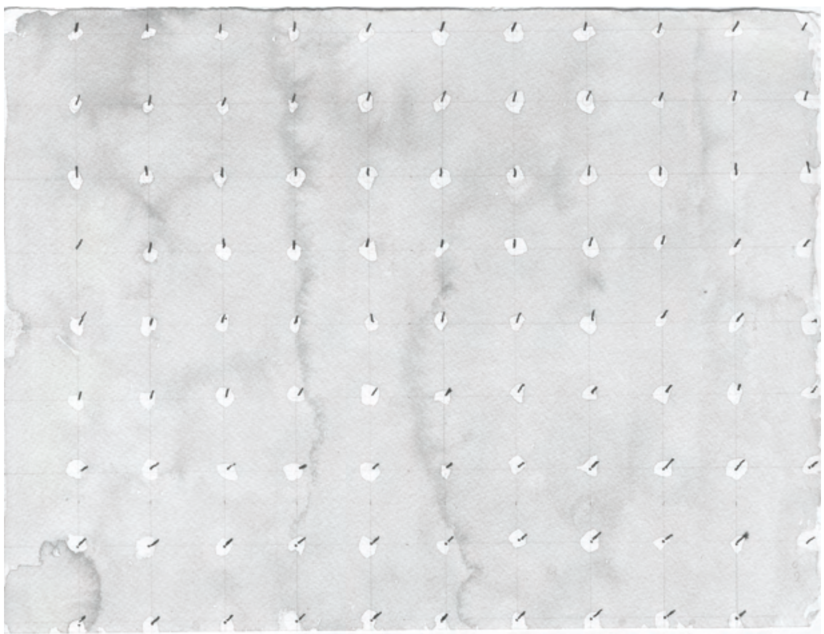
To design *with wind* is to work with a medium that has vast consequences across radically divergent spatial and temporal scales (Figure 1.7). Atmospheric phenomena such as turbulence occur at spatial scales as small as several millimetres, changing over the course of seconds or minutes, while global circulation patterns can operate at tens of thousands of



1.3

1.3 *Wind Grid* drawing surveys. The steel poles recorded other measures about the rise and fall of the earth, the inconsistent growth of crops, and the banks and drifts of snow. Air is, after all, one of many interrelated topographies, each a function in some way of the vagaries of wind and the obstacles that shadow it. While the site was not visible as a totality, the column of air surrounding each steel pole offered insights into subtler microclimatic conditions.

1.4 *Wind Grid* ink wash drawing. The drawing integrates moving water to represent moving air. Subtle pooling captures flow as a diffuse condition that contrasts the fixed vectors of air movement indicated at each grid point.



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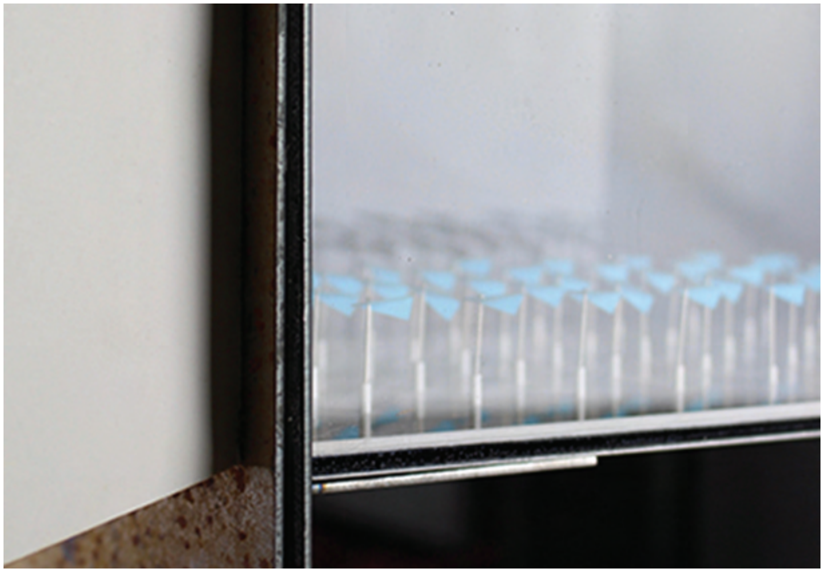
1.5 Photograph of the House on Limekiln Line. The *Wind Grid* installation was one of many studies that informed the design of the house. The saltbox roof pushes a heavy shoulder towards the prevailing westerly winter winds. The north and south façades are more porous, with operable windows that facilitate cooling effects of natural ventilation from southerly winds in the summer. A deck walk that extends into the landscape acts as a datum to the many shifting topographies beyond. Photograph: Shai Gil Photography.

1.5

1.6 Detail photograph of wind tunnel prototype 4. The Limekiln Line site acted as a notional wind tunnel, channelling and speeding up air movement through bounded forested edges. Subsequent questions raised by working with scale airflow models such as wind tunnels form the foundation for this book. What would a real wind tunnel reveal about air movement patterns, their tendencies and flow characteristics? What kind of architecture might an understanding of these principles reveal?



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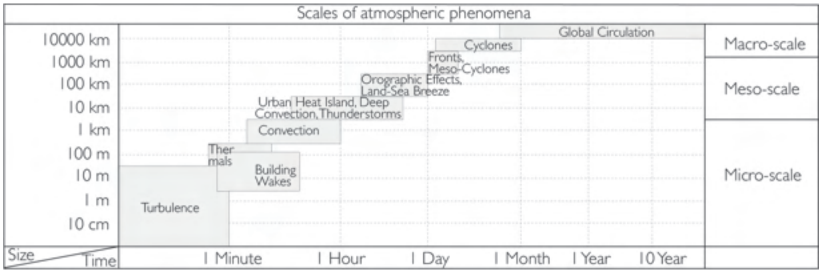

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1.7 Diagram illustrating the spatial and temporal scales of atmospheric phenomena. Drawing by Saman Soltani based on a table by Blocken (2014).

kilometres over spans of several years (Blocken 2014). Within the built environment, air movement impacts thermal comfort; it constructs microclimates; it effects structural performance and material endurance; and it can either reduce or increase dependence on mechanical heating and cooling through natural ventilation. At meso- and macro-scales, the shifts and courses of wind determine the path and distribution of airborne particulates such as dust, sand and snow, as well as of airborne contaminants. As global weather patterns become more erratic, wind drives many catastrophic events such as the spread of wildfires, the intensity of hurricanes and floods, and the extent of erosion and desertification.

I refer to wind – the natural movement of air due to differences in pressure – as a moving material system throughout the book because it has distinct physical characteristics. However, it is not even clear whether wind is a material or a thing at all. Aesthetic scholar Tonino Griffero describes wind as a 'quasi-thing', with particularly ineffable material characteristics. Unlike more conventional architectural materials, 'The wind is not edged, discrete, cohesive, or solid … nor does it properly possess spatial sides' (2020, 34). The temporalities of wind are nebulous. Wind is intermittent and, as Griffero notes, wind does not age, degrade nor 'show any temporal patina' (2020, 34). Wind also shares characteristics of philosopher Timothy Morton's hyperobjects. Hyperobjects are ecological objects such as global warming, the biosphere or dust storms that operate at expansive temporal and spatial scales far beyond that of the individual human. Hyperobjects are not even really objectival because they lack distinct part–whole relations. Like many environmental systems, wind is immersive, omni-present, expansive and without clear centre or boundary. Fundamentally, wind drives and shares properties with many environmental processes that are complex, diffuse, expansive and unpredictable. Wind can therefore act as a proxy for many environmental processes across many timeframes and at many spatial scales.

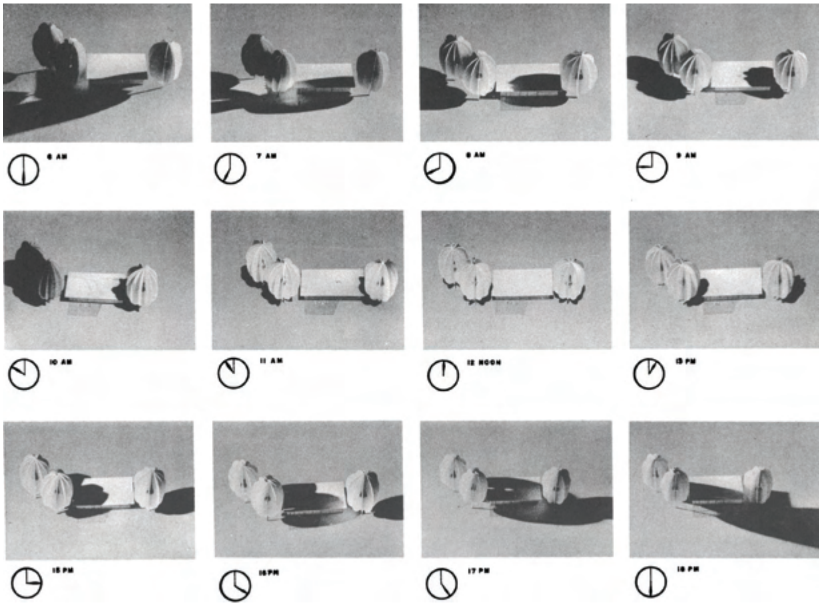
The term 'environment' takes on many meanings depending on context and theoretical framing. The 'environment' of the 'built environment' is distinct from that of the 'environmental movement' which is distinct from an 'environmental factor'. They all, however, refer broadly to surroundings or things outside, beyond or in between us and other objects in the world. Even this tidy description is fraught because it calls to question many foundational concepts about human experience, what constitutes an object and how we might describe the 'stuff' in between the two. To fill in some of these gaps, British anthropologist Tim Ingold has carefully traced philosophical frameworks for making sense of what constitutes an environment and what makes that constitution unique to humans, exploring the contours of James Gibson's concept of affordance, Jakob von Uexküll's *Umwelt*, Gilles Deleuze's lines of becoming, to more recent understandings of environmental inhabitation as taking place within 'fluid space'. Ingold concludes with his own theory: 'In short, to perceive the environment is not to look back on the things to be found in it, or to discern their congealed shapes and layouts, but to join with them in the material flows and movements contributing to their – and our – ongoing formation' (2011, 88).

Hélène Frichot's definition of environment in *Creative Ecologies* is a useful starting point for understanding how the term is used throughout this book. Frichot notes that: 'Environment is what unfurls when the architect or creative practitioner turns her back to the built object – which is an environment of a special sort, contained, "well-tempered" (Banham 1984) and controlled – and witnesses another point of view' (2019, 21). She suggests that, on the one hand, the environment is something that is *out there*, that operates according to temporal and spatial logics often beyond immediate cognitive grasp. It is what we see when we turn our backs to buildings or squint our eyes and look past them. It is a source of wonder, awe and terror. It is beyond our grasp, yet within our control. On the other hand, the environment is something *in here*, also around us, but bound by the enclosures of our buildings. Here, environment is controllable through our technological systems, our airtight building envelopes, our energy-intensive HVAC systems and our high-tech clothing. Frichot acknowledges the duality of these two environments and all the contradictions that they entail. But she also invites us to witness the world from another point of view, to squint our eyes and see beyond the dominant figures of buildings in this case, for, in doing so, we invite other worlds and ways of thinking into our lives. We do this not to resolve complexity but to better understand it from another vantage point. It is in the spirit of Frichot's characterisation and the dualities of understanding environments as being both 'out there' and 'in here' that I use the term 'environment'.

Environmental models

What is an environmental model? The term is used throughout this book in the absence of an existing, more established term in architecture specifically. The term *environmental model* has currency in scientific disciplines such as ecology, hydrology and geology, where it refers to physical modelling or digital simulation of dynamic natural processes for analytic and predictive purposes. Some landscape architects build on these scientific methods, modelling environmental systems as a means of monitoring, analysing or designing in response to watershed management, urban heat-island effects, erosion and sedimentation patterns, and storm-surge effects, among other things.

In the context of the discipline-specific work featured in this book, I define environmental models as *instruments which create controlled environments that make the phenomena of airflow visible*



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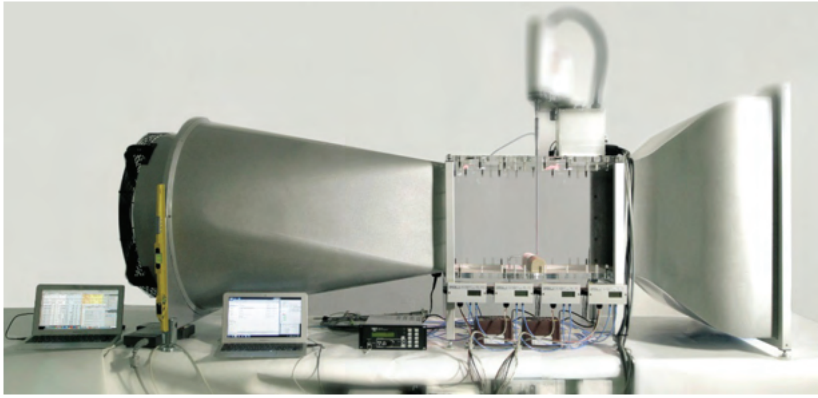
1.8 Victor Olgyay, *Summer Shading from Dawn to Dusk*, from *Design with Climate*, 2015 (2nd ed). Olgyay incorporated a range of empirical model experiments, supplemented with diagrams and numeric analysis, to develop a bio-climatic design methodology in his canonical environmental design textbook. Princeton University Press, reproduced with permission.

in relation to an architectural model. This is a working definition, and the broader contours, origins and significance of these terms – instrument, controlled environment, phenomena, architectural model – are explored throughout the book. Fundamentally, environmental models can be read at several scales: the one-to-one scale of the instrument as a tectonic artefact; the scale set by the architectural model on the testing bed; and the ambiguous scale of the controlled space of air and water flow. Each scale offers new vantage points for thinking about the dialogues between buildings, instruments, people, architectural models and the environments within which they are immersed.

Environmental models share a lineage with engineering experimentation devices. In the late nineteenth and early twentieth century, wind tunnels, water tables and flumes were devised to test hydrological and aeronautical principles primarily for vehicular movement – of boats and planes. Gustav Eiffel is credited as being the first to use wind tunnels to test wind loads on buildings, in 1908. In subsequent decades, understandings of turbulent flow and boundary layer characteristics, which are crucial for understanding airflow around and through buildings, were refined (Phillips and Soligo 2019). In the 1950s and 1960s, many schools of architecture developed dedicated environmental experimentation facilities. For example, Princeton, MIT and Columbia in the United States used heliodons (which simulate solar trajectories) and wind tunnels to design solar homes and to hone bioclimatic design principles (Figure 1.8). In the same period, in the United Kingdom, government-sponsored investigations by the Building Research Establishment (BRE) used wind tunnels to assess exterior pedestrian-level airflow patterns around mid- and high-rise buildings. Some schools of architecture have retained active environmental testing facilities, but research has generally shifted beyond basic design principles of form, aperture locations and orientation to more sophisticated and increasingly specialised concerns. For the most part, physical experiments focusing on urban airflow and building ventilation by architects have been eclipsed by digital simulation. The first engineering applications of computational fluid dynamics analysis of buildings took place in the 1970s, but CFD did not appear in the field of architecture specifically until the 1990s. Rapid increases in computer speeds and software refinements have led



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to an extensive array of CFD packages now available (Phillips and Soligo 2019). CFD is largely mainstream today with both commercial and open-source versions, but it presents challenges for non-specialists, explored in more detail in Chapter 3.

While wind engineers rely on computational strategies, physical experiments are still commonplace for testing building ventilation and urban airflow patterns. Such experiments are often completed in tandem with CFD and on-site experiments, which are seen as complementary endeavours. Some engineers argue that CFD modelling is less accurate and reliable than wind tunnel tests due to challenges with solving equations associated with turbulent flow (Phillips and Soligo 2019). Regardless of method, engineers tend to focus on acquiring numeric results that can be scaled up to predict full-scale performance to a high degree of accuracy. Building models placed in wind tunnels, for example, are generally equipped with pressure sensors from which air speed is then calculated. This data is applied to scaling formulas to determine equivalent results at full scale.[1]

The engineering focus on numeric precision is incongruent with early architectural design speculation. For the architect studying airflow in the early stages of design, only a general understanding of basic flow patterns is necessary. Moreover, reconciling scale effects in small, low-tech models such as those featured in this book is not viable. Research conducted by Hitchins and Wilson (1967) using wind tunnels found that if architectural models are geometrically accurate, general airflow patterns in a wind tunnel were consistent enough to give a reliable indication of airflow patterns. This applies to bluff bodies, geometries with sharp edges, since flow separates at the edges similarly across scales.

For the architect, working with environmental models is a messier, 'designerly' variant of more conventional engineering experimentation. Engineering research tends to follow a model–measure–analyse methodology.[2] A physical model is placed in the testing bed, a series of tests are conducted that generate numeric results which can be used to assess effects at full scale, and then these results are analysed. Architectural design is distinct in that it is often non-linear, recursive, iterative and lacking rigidly defined controls and variables. Maider Llaguno-Munitxa's research at Princeton University, which integrates robotics with wind tunnels, critiques the conventional model–measure–analyse approach (Figure 1.9). In her research, a robotic arm alters elements of architectural models in the testing bed while the

1.9 Photograph of Maider LLaguno-Munitxa's wind tunnel with integrated robotic arm. Robotic integration enables iterative, real-time material studies, challenging the conventional linear 'model-measure-analyse' methodology that characterises conventional engineering experimentation. Springer Nature, reproduced with permission.

1.10

1.10 Design Earth, *Pacific Aquarium Project,* installation at the Oslo Architecture Triennale. Each aquarium in the installation contains a speculative design proposal related to deep-sea resource extraction for a section of the Clarion-Clipperton Zone. The installation makes legible planetary-scale concerns within the objectified space of the fish aquarium, establishing a critical dialogue between the models and their co-constructed environments. Courtesy of Design Earth.

wind tunnel is in operation. This automation enables iterative, real-time testing of a range of spatial and material strategies for how building form and materiality impact airflow around and between buildings. The California-based research group Future Forms (previously Future Cities Lab) also conducts a designerly variant of experimental research using 'live models'. Their installations often translate real-time environmental data into dynamic physical artefacts that respond to this data. They conceive of these live models not as simulations or even as scale models, but instead as 'conceptual frameworks for architecture' (Kelly and Gattegno 2012, 141).[3]

While designing wind tunnels or water tables specifically is rarely the topic of architectural design scrutiny, there are contemporary designers whose work offers useful insights about working with air and water as constituent design materials across scales. For the architectural designer, environmental models enable speculation beyond simply examining the effects of airflow around the architectural model. This trait makes them particularly valuable as tools for design speculation about urgencies associated with the climate crisis. These concerns range from the pragmatic – the design of low-energy buildings reliant on natural ventilation – to the theoretical – speculation about what it means to design within diffuse, volatile environmental systems that operate all the way up to the planetary scales.

Design Earth's *Pacific Aquarium Project* highlights the role that environmental models can play as narrative devices that transcend radical scales of design speculation (Figure 1.10). In the *Pacific Aquarium Project*, nine scale models are submerged in individual fish aquariums. Each represents a design intervention within sections of the Clarion-Clipperton oceanic rift. Collectively, the projects make legible scales of environmental degradation otherwise beyond cognitive reach, while also reinforcing the historic role aquariums have played in the natural sciences as objects of reverie (Ghosn and Jazairy 2017). Operating at more conventional architectural scales, Lydia Kallipoliti's *Microclimates* project, included in the *Microcosms and Schisms* exhibition at the 2021 Venice Biennale, similarly uses physical models of notionally constructed environments to make a political statement (Figure 1.11). The project highlights some of the fantastically strange, yet unfortunately real, interior microclimatic constructions

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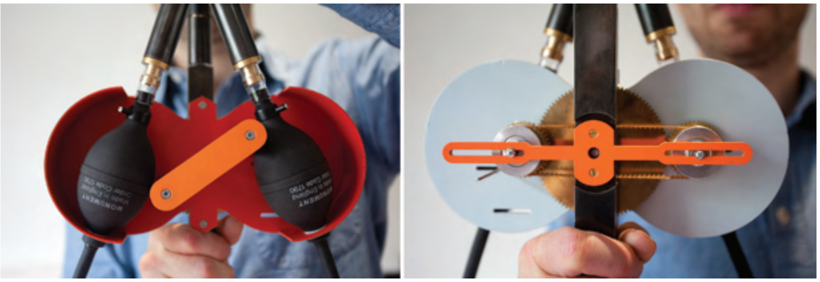

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1.11 Lydia Kallipoliti with Doosung Shin, *The Psychrometric Interior*. This model was part of the project *Microclimates*, exhibited at the Venice Architecture Biennale 2021. Courtesy of Lydia Kallipoliti.

1.12 Smout Allen, *Air Instrument*. The device integrates rubber pumps, referred to as 'twin glands' with painted and blued steel and machined brass components. Part of their *Envirographic Instruments* series, the air instrument offers a tectonic approach for working with air as a constituent design material. Courtesy of Smout Allen.

of late modern capitalism. Each microclimate model features an architectural space, such as a partitioned office or an enclosed atrium, built onto the carriage of a model train car and then encased in a plastic dome. The models critique the codifications of homogenizing thermal comfort standards and the ironies of constructing interior tropical gardens in standard office buildings, among other related concerns. Like the aquariums used in the *Pacific Aquarium Project*, *Microclimates* draws from aesthetic experiences associated with miniaturisation, in this case of model trains, which are objects of reverie.

Smout Allen's *Envirographic Instruments* shift focus to tectonic concerns raised by constructing environmental models (Figure 1.12). Designed as site-specific instruments for the Severn Estuary, one instrument registers air and the other water. Constructed of rubber hoses, air and water valves, manual air-pump 'glands', painted steel and machined bronze, the instruments sensitively respond to the pressure and movements of fluid materials. The instruments subsequently informed the framing of architectural design speculations on the site as technological interventions with the geomorphological, hydrological and atmospheric systems of the River Severn.

Finally, there are projects, such as Catty Dan Zhang's *Vents* installation at the University of North Carolina at Charlotte exhibition *SEE-ING: The Environmental Consciousness Project* which rely on techniques of flow visualisation to make interior meteorological conditions visible (Figure 1.13). Using smoke and strategic lighting, the project challenges conventional understanding of space as inert void. In *Vents*, a series of inverted umbrellas form an overhead canopy that puffs rings of fog which respond to datasets of wind speeds recorded over a seven-day period for Hurricane Florence. The installation translates an extreme meteorological event elsewhere into a constructed interior of atmospheric effects. Careful control of lighting through backlit screens and overhead, cool LED lights within an otherwise dark space further amplifies the

1.13

1.13 Catty Dan Zhang, *Vents*, installation at the *SEE-ING: The Environmental Consciousness Project* exhibition at UNC Charlotte. Through careful calibration of light and vapour, flow visualisation techniques are used to amplify the effect of constructed interior meteorologies. Vapour rings correspond to weather data associated with an extreme weather event elsewhere, translating the interior of the exhibition into a space of heightened atmospheric effects. Courtesy of Catty Dan Zhang. Photograph: Ben Premeaux, 2018.

visualisation of airflow patterns registered through the fog rings.

This sampling of architectural practices and approaches highlights the range of roles that environmental models can productively play in the design process: they are objects of speculation about building scientific processes; they are tectonic assemblies of environmental mediation; they are objects that tell stories about environmental degradation; and they are artefacts that make the construction of interior weather legible through flow visualisation.

Architectural models

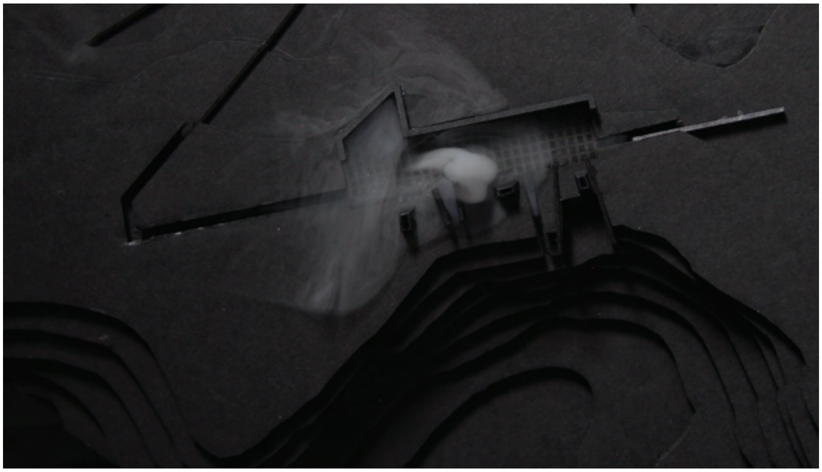
Fundamentally, environmental models are *models* – distillations of complex conditions into artefacts that are legible at the scale of the hand and the body. As scale representations, models establish important dialogues with their referents. Much theorisation about architectural representation focuses on the nature of the correspondence between a representation (in this case a model) and its referent. Are they separate and distinct? Are they one and the same? What do models tell us about the world and what does the world tell us about models? Environmental models focus these questions specifically on environmental topics – about mediation, degradation, contamination and containment – and the sites (real or imagined) in which these processes play out.

An interview between historian of science D. Graham Burnett and architect Daniel Solomon published in *Models: 306090* offers a useful framework for considering the dialogue between an environmental model and its *target system*, the term used in history and philosophy of science that is equivalent to the term 'referent' in architectural theory. The interview highlights some attributes of environmental models that both build on and disrupt conventions of models in architectural representation. In the interview, Burnett reflects on the historical use of physical scientific models within the context of contemporary architectural design, making a distinction between *analogical* models and *ontological* models. Analogical models, he suggests, are models whose central attributes apply by analogy to the physical traits or attributes of the scaled thing that is being modelled. In other words, the model is understood as distinct from, but analogous to, aspects of the world, or the target system, it represents. The connection between the model and its target system(s) are based on the juxtaposition of similarities in appearance or behaviour, and these similarities make the model analogous to the conditions in the world that the model represents. Ontological models, on the other hand, start to blur distinctions between model and target; rather than operating by analogy, traits converge. Ontological models cause the physical traits of the world being modelled 'to be made manifest – and hence allow[s] for the revealing, touching, tweaking, or accessing of … the *actual forces and stuff* at issue' (Burnett and Solomon 2008, 44). In other words, ontological models start to make more direct material or causal alignments between model and world being modelled. They even have the capacity to inaugurate paradigm shifts in how we understand the workings of the world.

Burnett goes further to suggest that the distinctions between analogical and ontological models are less crucial than the dialogues between the two. He suggests that often a productive shift occurs when models move from being analogies to being *something more*, yielding insights to the workings of the world that one would not have access to otherwise. To illustrate this idea, Burnett uses the roughly four-hundred-year development of clock-making that eventually lead to a conception of a clockwork-universe as a prime example of the slippage between analogical and ontological modelling. Initially understood as a timekeeping device that modelled by analogy the orbiting of the Earth around the Sun, the clock eventually became a conception of how the world literally works: 'Somewhere in there a mess of thinking folks go from having built a clockwork model of the visible features of celestial dynamics to reasoning that the celestial dynamics themselves may well be a big clockwork' (Burnett and Solomon 2008, 45). The model, in this case a clock, which replicates the cosmic workings of the world in miniature, shifts from being a representation of the cosmic world to being understood as that world. This shift in understanding facilitated by the model instigated a paradigm shift in thinking about the actual workings of the world from one governed by the will of God to one governed by the mechanistic laws of science.

Burnett's analogical/ontological model distinction informs ways of thinking about environmental models within the broader context of architectural representation in three ways. First, it offers a framework for discussing how models converse with their targets, situating models within a broader context beyond the internal workings of the model itself. Models are, as visual artist Olafur Eliasson puts it, co-producers of reality.[4] The relationship between *good* models and targets is dialogic; it is one that *shifts*. The model informs conceptions of the world as much as the world informs conceptions of the model. Models are, after all, both physical artefacts and mental ideals. Working with environmental models prompts questions about how the models we make might inform ways of thinking about the ideals to which we aspire.

Second, the analogical/ontological model distinction highlights the material significance of environmental models. They allow for the 'revealing, touching and tweaking' of the 'actual forces and stuff' at work in the model, uncovering the world of fluid dynamics in a way that is material and intuitively legible (Burnett and



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Solomon 2008, 44). Air pressure induced in wind tunnels replicates air pressure found at 1:1 in the world. Plumes of buoyant airflow in filling-box models follow the same natural laws as those at full scale within a building. These force-exchanges transcend being simply stand-ins for the actual forces they represent – *they are the same forces* – making them remarkable tools of material exploration.

The messy materiality of environmental models makes them productive as design tools, but this messiness challenges one trait conventionally valued in architectural models – their material muteness. The 'messiness' of models has historically been suppressed. Models have often been considered inferior to drawing in theories of architectural representation. The perceived inferiority can be traced to the Renaissance when a dissociation occurred between design and construction. Design took place in the clean, refined studio through the 'gentlemanly' act of drawing. Construction and material exploration such as model-making took place in the grubby, material world of the construction site or workshop (Starkey 2005). Moreover, models were often valued for their emphasis on form rather than materiality. In *On the Art of Building in Ten Books*, for example, Alberti warns against using unnecessary decoration in architectural models. He suggests that the materiality of the model and its means of construction should be subdued, noting: 'Better then that the models are not accurately finished, refined, and highly decorated, but plain and simple, so that they demonstrate the ingenuity of him who conceived the idea, and not the skill of the one who fabricated the model' (Alberti 1452 cited in Smith 2004, 28).

One consequence of the division of labour between model and drawing was that drawing gained a higher intellectual status than the model, a status that has largely persisted. However, as architectural theorist Robin Evans reminds us, some architectural conditions simply resist being drawn. Evans uses the palpable luminosities of James Turrell's light rooms as an example of one such condition. He notes that

> not all things architectural (and Turrell's rooms are surely architectural) can be arrived at through drawing … if judgement is that these qualities in and around the shadow line are more interesting than those laid forth clearly in drawing, then such drawing should be abandoned, and another way of working instituted.
>
> (Evans 1996, 159)

1.14 Model photograph of *GeoThermoHaptic*, a speculative project completed for a visitors' centre in northern Iceland. The project is designed as an experiential choreography, alternating between immersion within and hovering over the geological and thermal substrate upon which the Icelandic volcanic landscape rests. Inclusion of smoke as an analogue to steam in the model reinforces that pressure, heat and steam are constituent project materials. Project completed with Calum Rennie and Laura Haylock. Photograph: Calum Rennie.

1.15

1.15 Interior model photograph of *GeoThermoHaptic*. In the design, geothermal steam released from valves embedded in the excavated floor makes geological processes visible. The model, which incorporates wool, crushed rock and smoke, contrasts the conventional 'materially-mute' architectural model. Project completed with Calum Rennie and Laura Haylock. Photograph: Calum Rennie.

Atmospheric qualities, thermal exchange and air movement are similar architectural qualities that demand another way of working (Figs. 1.14, 1.15).

Finally, the analogical/ontological model distinction offers a way of describing working with architectural models as part of an iterative design process. Often, discoveries in the design process are made through accidental substitutions, by conceptual inversions and by shifting vantage point.[5] In these moments, sometimes profound reconceptualisations emerge. This book explores these dialogues between the constituent elements of environmental models – instrument, phenomena, architecture – and between models and their target systems. The book makes the case that conceptual connections between a model and its target system are strongest when the relationship between the two is not fixed or rigid, but instead oscillates through the process of design.

Overview

This book establishes insights learned through making and critical analysis. It moves in time between past and present. It works across many scales. Chapter 2 profiles 10 original prototypes, highlighting their role as mechanical artefacts that create controlled environments of legible flow. Chapters 3, 4 and 5 each tell the story of a single precedent model that has largely gone overlooked in the histories of architectural design and building science. The case studies range historically from the Industrial Revolution to the post-war period, a span of time in which the climate control of buildings emerged as a techno-scientific project. They establish some of the origins for contemporary design concerns related to flow visualisation, thermal comfort and building climate control. While they are organised non-chronologically, they are what architectural historian Daniel Barber refers to as 'epochal, recursive projects'; each is an 'object from the past that describes a relationship to climate with unanticipated relevance to the present and future' (Barber 2020, 9).

Chapter 2 is a visual catalogue of four wind-tunnel, four water-table and two filling-box prototypes. Each makes airflow associated with either pressure or buoyancy-induced differentials visible. This chapter focuses primarily on fabrication techniques for making environmental models and techniques for visualising flow. For those interested in building their own environmental models, this chapter offers relevant resources and techniques for doing so, often adapting material and fabrication techniques from engineering and DIY resources to those more readily available in architecture workshops.

Chapter 3 features French polymath Étienne-Jules Marey's wind tunnel and associated smoke-stream photographs. Marey was a prolific inventor best known for the photographic techniques he devised to capture incremental views of birds in flight. Towards the end of his career, Marey constructed wind tunnels that used smoke streams to visualise airflow around wing profiles, marking a shift in his research from the subject of flight to the medium of flight. The smooth, moving lines of smoke that erupt into trailing eddies and vortices around linear and cambered profiles have been celebrated as photographic achievements. While the curling vortex trails in Marey's photographs are beguiling, this chapter reveals that there is more to be learned about air movement by focusing instead on the steady, continuous streamlines of undisturbed smoke.

Chapter 3 examines Marey's wind tunnels through two frames: first, through the lens of the camera and, second, as a spectator in Marey's physiological research station. The initial frame focuses on the phenomena of airflow and its materialisation through smoke streams. Marey's work is situated within a broader context of early developments in flow visualisation, calling to question: what makes a good flow visualisation *good*? And what does a good flow visualisation tell us about the properties of air as a moving material system? The second frame of reference is as a spectator in Marey's physiological research station, observing the wind tunnel itself. While the wind tunnel appears a robust mechanical assemblage, it is in fact a delicate instrument that inadvertently registers external disturbance, revealing air's extreme material sensitivity. This chapter concludes with photographs of my water-table and wind-tunnel prototypes, highlighting the challenge of creating the steady lines of smoke that appear so effortless in Marey's photographs.

Chapter 4 features Victor and Aladár Olgyay's thermoheliodon, an incomplete experiment published in the appendix of Victor Olgyay's canonical *Design with Climate: A Bioclimatic Approach to Architecture*, published in 1963. The thermoheliodon was intended as an advancement of the heliodon, simulating wind flow and thermal conditions in addition to solar trajectories on physical models. The thermoheliodon highlights dialogues between models and their target systems, focusing on ideals of architectural environmental mediation that emerged in the US during the post-war era surrounding the climate control of buildings.

The thermoheliodon reflected two emerging post-war, data-driven conceptions of environment: variable exterior and controllable interior. It also reflected two conceptions of architecture that mediate these environments: one predicated on adaptation and the other on encapsulation. One is a filter; the other is a bubble. Through a deliberate misreading of the thermoheliodon as an architectural model, Olgyay's bioclimatic designs are contrasted with those predicated on creating a hermetically sealed interior. These two models of environmental design have persisted, largely informing discourse about the environmental management of buildings today. This chapter concludes with photographic documentation of an exhibition of my prototypes, reflecting on the nested environments that environmental models – and by inference all objects, infrastructure and furnishing within buildings – are implicated in.

Chapter 5 examines Scottish physician David Boswell 'The Ventilator' Reid's convection experiments, published in 1844, in one of the first comprehensive textbooks of building ventilation: *Illustrations of the Theory and Practice of Ventilation*. The book, peppered with the kind of arrow-overlaid environmental diagrams ubiquitous in technology textbooks, incorporates two experiments that illustrate the principles of convection. Using a glass test tube and a glass 'tubular apparatus', coloured water and a naked flame, the experiments illustrate that air moves due to differentials in temperature, a principle he applied to many of his ventilation strategies. The utter simplicity of Reid's 'tubular apparatus' sits in contrast to the elaborate mechanics of Marey's wind tunnels and the Olgyays' thermoheliodon, lending itself to being read as an architectural model of interconnected spaces.

Reid's convection experiments prompt ready speculation about architectural models as vessels of atmospheric exchange in the early moments of the codification of building ventilation practice. They make visible principles underpinning a third model of environmental mediation present today: buildings as thermodynamic objects. This chapter explores the emergence of contemporary concepts such as thermal asymmetry, thermal imbalance and alliesthesia, all of which rely on thermal variability as drivers of spatial organisation. This chapter concludes with photographs of my filling-box models, highlighting an important distinction between models as physical artefacts and models as mental ideals. Physical models have material defects. They leak, unlike the ideals they represent. Filling-box models leak, and they leak somewhere, initiating a cascading series of exchanges that situate models within a much wider atmospheric context.

Chapter 6, the concluding chapter in this book, reinforces the significance of environmental models as tools for multiscalar architectural speculation about pressing environmental concerns. It asks: what is the target of our environmental models now and how can environmental models reflect these complexities? The chapter outlines three recurring terms of reference raised by case studies featured in the book – resistance, diminution and buoyancy. It explores what these terms offer for thinking about architecture's model environments today, especially given the challenges of climate breakdown and its associated injustices, as well as aerosol virus transmission associated with the COVID-19 pandemic.

Seen through the distilling lens of the architectural model, this book is an episodic and far-reaching exploration of dialogues buildings have with their environmental surroundings. The book covers topics including: how the material properties of airflow are revealed or concealed through flow visualisation strategies; how diverging building climate-control strategies are manifest architecturally through building enclosure; and how expanding models of thermal comfort drive the formation of architectural form. Each topic establishes some of the origins of architectural concerns associated with urgencies of designing today. The book reveals the potent ability for models to both reflect prevailing cultural views about the world and to even go reshape those views. It examines models as physical artefacts and models as mental ideals and reveals how environmental models open design insights across scales from the seam (that leaks) to the body (that feels) to the building (that mediates) to the world (that immerses).

Notes

1. Ventilation resources for architects also tend to stress that the value of working with physical experiments is that they yield quantitative results. As one example, in the comprehensive and informative book *Designing Spaces for Natural Ventilation: An Architect's Guide*, Francine Battaglia and Ulricke Passe describe some advantages of using wind tunnels, but lament that 'the drawback is that the dynamics of the air flow within the building is not measured' (2015, 281).
2. Bruce Archer offers a useful distinction between the disciplines of design and technology. He suggests that 'if technology is "knowing-how", then design is "envisaging-what"' (Archer, Baynes and Roberts 2007, 19). While their work focuses on structural concerns, the form-finding models by Antoni Gaudi, Heinz Isler and Frei Otto operate somewhere in this middle ground between technical invention and design speculation.
3. Several contemporary landscape architects use physical hydrological models to enable design speculation. Bradley Cantrell and Justine Holzman's book *Responsive Landscapes: Strategies for Responsive Technologies in Landscape Architecture* (2016) outlines a range of approaches of working with hybrid digital and physical models. See also Skylar Tibbits's wave-tank studies for the *Growing Islands* (Self Assembly Lab, n.d.) project in the Maldives and Catherine Seavitt-Nordenson. *On the Water: Palisade Bay* (2010), model studies featured in the next chapter.
4. Olafur Eliasson goes so far as to dissolve distinctions between model and world altogether, noting:

   > Previously models were conceived as rationalized stations on the way to a perfect object. A model of a house, for instance, would be part of a temporal sequence, as the refinement of the image of the house, but the actual and real house was considered a static, final consequence of the model. Thus the model was merely an image, a representation of reality without being real itself. What we are witnessing is a shift in the traditional relationship between reality and representation. We no longer progress from model to reality, but from model to model while acknowledging that both models are, in fact, real.... Rather than seeing model and reality as polarized modes, they now function on the same level. Models have become co-producers of reality.
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   > (2008, 19)

   Eliasson is describing a historic shift in the epistemological status of models. He suggests that models have moved from being conceived of as static representations of the world to being active agents in constructing understandings of it.
5. Peter Eisenman's 1976 *Idea as Model* exhibition at the Institute for Architecture and Urban Studies marked an important conceptual shift in the role and value of the architectural model. The exhibition catalogue notes that Eisenman was guided by

   > a long-standing intuition ... that a model of a building could be something other than a narrative record of a project or building. It seemed the models, like architectural drawings, could well have an artistic or conceptual existence of their own, one which was relatively independent of the project that they represented.
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   > (Pommer cited in Frampton and Kolbowski 1981)

   Many useful resources elaborate on the conceptual value of working with physical models. A few highlights include Karen Moon, *Modeling Messages: The Architect and the Model*, 2005; Marco Frascari, Jonathan Hale and Bradley Starkey (editors), *From Models to Drawings: Imagination and Representation in Architecture*, 2008; Mark Morris, *Models, Architecture and the Miniature*, 2006; Albert Smith, *Architectural Model as Machine: A New View of Models from Antiquity to the Present Day*, 2004; and Patrick Healy, *The Model and Its Architecture*, 2008.