BUILDING DYNAMICS: EXPLORING ARCHITECTURE OF CHANGE

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Abstract. This paper surveys essential concepts and significant past and current projects that deal with interactive, responsive environments, i.e. buildings that can change their configuration, appearance, and environmental conditions in response to patterns of occupation and context (and in return can shape those too). It discusses what may seem to be rather obvious: responsive, adaptive, flexible, etc., architectures are all about change, which in turn, is all about time. The principal argument is that change in architecture is far from being adequately addressed or explored theoretically, experimentally, or phenomenologically.

1. The Arduino revolution

In 2005 an inexpensive open source microcontroller board called Arduino was released in Italy. It could be connected easily to a variety of sensors detecting light, motion, touch, sound, temperature, etc. and by reading input from them could be made to "sense" the environment. It could be also connected to all kinds of actuators, such as lights, motors, and other devices, and could control them to "affect" that same environment. It also came with a simple development environment for writing software that could interpret the received input values from the sensors and produce output instructions that would control the operation of the actuators. Since its release, hundreds of thousands of these inexpensive electronics boards have been sold worldwide, enabling enthusiasts to create all sorts of interactive objects and environments. Arduino boards (figure 1) also found their way into the schools of architecture worldwide, sparking the imagination of students and reigniting the vision of dynamic built environments that could change on the fly. Buildings could thus become "alive" by sensing what was happening in and around them and by adjusting their spatial configuration and the environmental conditions on the fly. The dynamically changing buildings, imagined in science fiction novels from the 1960s and 1970s, started to emerge as a not-so-distant technological possibility.

Figure 1. Arduino microcontroller board

2. Towards Psychotropic And Emotive Houses

> "It was a beautiful room all right, with opaque plastex walls and white fluo-glass ceiling, but something terrible had happened there. As it responded to me, the ceiling lifting slightly and the walls growing less opaque, reflecting my perspective-seeking eye, I noticed that curious mottled knots were forming, indicating where the room had been strained and healed faultily. Deep hidden rifts began to distort the sphere, ballooning out one of the alcoves like a bubble of overextended gum." —J.G. Ballard, The Thousand Dreams of *Bellavista*

James Graham Ballard, the British novelist, describes in his short story "The Thousand Dreams of Stellavista" (1962), a "psychotropic house," a machine-like, mood-sensitive house that responds to and learns from its occupants. The imagined sci-fi house is made from a material Ballard referred to as "plastex," a combination of plaster and latex that allows the house to change its shape as needed. Furthermore, the house features, distributed over it, many "senso-cells," which are capable of "echoing every shift of mood and position of its occupants, such that living in one was like inhabiting someone else's brain."

While Ballard's "psychotropic house" belongs to science fiction, the "E-motive House" by Kas Oosterhuis (2002) edges closer to contemporary technological and material reality. Oosterhuis describes a responsive, interactive house that can develop its own emotions, "a house with a character of its own, sometimes unyielding, sometimes flexible, at one time sexy, at another unpredictable, stiff and unfeeling." The goal is to create an "emotional relationship between the house, its occupiers and the elements." The E-motive House can be a "reactor" as well as an "actor," where the "acting will be made possible by a cooperative swarm of actuators like pneumatic beams, contracting muscles and hydraulic cylinders." The house is also capable of reacting: "The movement of the users and the changes in the weather are registered by a diversity of sensors, and are translated by the brain of the house into an action." In this way, the inhabitants and the actuators of the house will develop a common language so that they can communicate with each other.

In 2003, Oosterhuis and his Hyperbody research group designed and constructed the Muscle, a working prototype of a programmable building (figure 2) that can reconfigure itself "mentally and physically." The Muscle is a pressurized soft volume, wrapped in a mesh of tensile Festo "muscles," which can change their own length and, thus, the overall shape of the prototype. The public connects to the prototype by sensors and quickly learns how the Muscle reacts to their actions; the Muscle, however, is programmed to have a will of its own, making the outcomes of interactions unpredictable. The ultimate goal of the project is to "develop an individual character for the Muscle." The Muscle has demonstrated that the E-motive House is not so techno-utopian—and that Ballard's "psychotropic" house could perhaps become a reality of our inhabitation in the future.

Figure 2. *Muscle* prototype of a programmable building by Kas Oosterhuis and his Hyperbody research group at TU Delft.

3. Towards Architecture That Is Adaptive, Flexible, Interactive, Responsive

A common thread that runs through Ballard's "psychotropic house" and Oosterhuis's E-motive House is a vision of an architecture in which buildings can change their shape, their form, the configuration and appearance of space, and environmental conditions—on the fly—in response to patterns of occupation and contextual conditions (and shape those, in return, too). Buildings will become adaptive, interactive, reflexive, responsive…

As the external socio-economic, cultural, and technological context changes, so do conceptions of space, shape, and form in architecture. Over the past decade, we have seen an increasing interest in exploring the capacity of built spaces to change (i.e., to respond dynamically to changes in the external and internal environments and to different patterns of use). Oosterhuis's Muscle is just one of many experimental projects that have been completed. The principal idea is that two-way relationships could be established among the spaces, the environment, and the users: the users or the changes in the environment would affect the configuration of space and vice versa; the result is an architecture that self-adjusts to the needs of the users.

The first concepts of an adaptive, responsive architecture where born in the late 1960s and early 1970s, primarily as a result of parallel developments in cybernetics, artificial intelligence, and information technologies, in general, and as a response to architecture's rigid, inflexible articulation of space and its configuration.

Gordon Pask set the foundations for interactive environments in the 1960s; he was one of the early proponents of cybernetics in architecture, whose concept of Conversation Theory, as a comprehensive theory of interaction, is particularly applicable today as various attempts are made to create constructive relationships between humans and machines (as in interactive architecture). Pask's ideas had a tremendous influence on both Cedric Price and Nicholas Negroponte, whose pioneering work in the 1960s continues to inspire; Pask worked with both Price and Negroponte.

Cedric Price was the first to adopt concepts from cybernetics and use them to articulate a concept of "anticipatory architecture," manifested in his Fun Palace and Generator projects. Nicholas Negroponte was among the first to propose in the late 1960s that computing power be integrated into buildings so that they could perform better. In his book Soft Architecture Machines (1975), he moved beyond the "architecture machines" that would help architects design buildings and proposed that buildings could be "'assisted,' 'augmented,' and eventually 'replicated' by a computer." The ambition was to "consider the physical environment as an evolving mechanism." In the last chapter, he made a prediction that "architecture machines" (in the distant future) "won't help us design; instead, we will live in them," echoing the sci-fi "psychotropic houses" of J.G. Ballard.

At roughly the same time that Negroponte was working on his "architecture machines," Charles Eastman (1972) developed the concept of "adaptive-conditional architecture," which self-adjusts based on the feedback from the spaces and users. Eastman proposed that automated systems could control buildings' responses. He used an analogy of a thermostat to describe the essential components: sensors that would register changes in the environment, control mechanisms (or algorithms) that would interpret sensor readings, actuators as devices that would produce changes in the environment, and a device (an interface) that would let users enter their preferences. That is roughly the component makeup of any reactive system developed to date.

Jean Nouvel's Institut du Monde Arabe, completed in 1989 in Paris, was the first significant, large-scale building to have an adaptive envelope (figure 3). The building's kinetic curtain wall, a technological interpretation in glass and steel of a traditional Arab lattice screen, is composed of some 30,000 photosensitive diaphragms that control light levels and transparency in response to the sun's location (the system no longer works due to mechanical problems). Hoberman Associates (led by Chuck Hoberman) is perhaps one of the best-known contemporary practices to have designed several kinetic, performance-based adaptive shading systems for building projects by firms such as Foster and Partners and Nikken Sekkei. More and more designers and firms are beginning to experiment with innovative sensing, control, and actuation technologies to create kinetic, adaptive performance-based systems.

In 2011 the “Adaptive Architecture” conference was held at the Building Centre in London. At this seminal event, convened by Michael Stacey, presentations were grouped into four thematic categories: Dynamic Facades, Transformable Structures, Bio-Inspired Materials and Intelligence, which could be considered as a taxonomy of current research efforts in this area. Chuck Hoberman and Craig Schwitter (of Buro Happold) launched in 2008 the Adaptive Building Initiative (ABI), with the aim of “designing a new generation of buildings that optimize their configuration in real time by responding to environmental changes;” most of their initial efforts were aimed at creating environmentally responsive building facades (for more information visit www.adaptivebuildings.com).

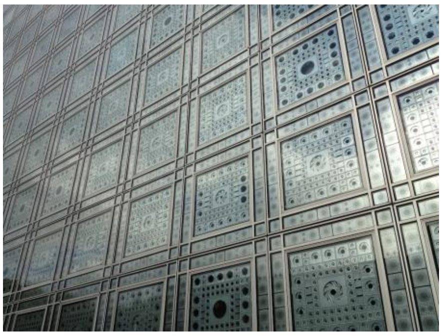

Figure 3. Kinetic curtain wall at Jean Nouvel’s Institut du Monde Arabe

In collaboration with Zahner Metals from Kansas, ABI has designed an adaptive façade system called Tesselate, a self-contained, framed perforated screen that consists of stacked panels that move and overlap, creating kaleidoscopic patterns (figure 4), which control light and solar gain, ventilation and airflow, privacy, and views. The Strata adaptive shading system is made of modular units that consist of telescoptic fins that can retract into a single slender profile or extend to form a nearly continuous surface (figure 5). The Tessellate dynamic perforated screen system was incorporated by the architectural firm WORKSBUREAU in the façade design for twin luxury spas (figure 6) that should become the gateway to the King Abdullah Financial District in Riyadh (construction is scheduled to begin in 2014). The system’s modules consist of three layers of perforated color-interference titanium, two of which are motorized, so that the perforated patterns create overlaps and thus regulate light and heat in a continuous reaction to external conditions. According to the designers’ estimates, this façade system should reduce the cost of cooling the building by 15 to 20 per cent.

Figure 4. Tesselate *adaptive façade system designed by ABI in collaboration with Zahner* Metals.

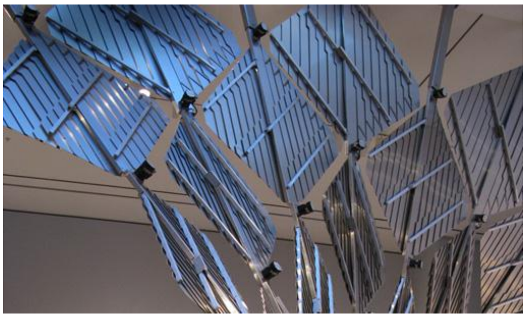

Figure 5. Strata adaptive shading system designed by ABI in collaboration with Zahner Metals.

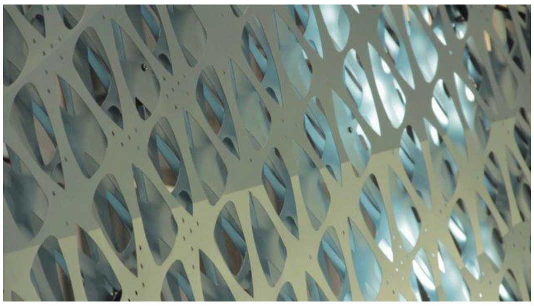

Figure 6. The KAFD Spas in Riyadh should feature an adaptive façade system designed by ABI and made by Zahner Metals.

In 2010 our research group, Laboratory for Integrative Design (LID), created iConic, a prototype of a building facade system comprised of mechanized, electronically controlled truncated conic modules (figure 07) that rotate independently, altering the orientation of elliptical apertures and producing different performative effects during the course of a day, from dynamic sun shading and regulating outward views to urban-scale performances across the exterior field. Even though various tests were performed on the rotating conic modules, the prototype started producing squealing, whirling, and scratching noises soon after it was publicly exhibited. The main challenge in its design was not the geometry, electronics or the actuation, but friction, which to this date remains an issue in almost all mechanically, i.e. motor-based actuation systems. Friction, i.e. the required frequent maintenance of malfunctioning apertures, is the primary reason that the kinetic façade on Jean Nouvel's Institute du Monde Arabe building is now "permanently frozen". It is also why designers of adaptive systems are looking into other ways of actuation besides motor-based ones, such as hydraulics, pneumatics, or material-based actuation.

The Media ICT building in Barcelona, designed by Enric Ruiz-Geli of Cloud 9, features a dynamic façade made of light-weight ETFE air cushions that provides for pneumatic sun shading (figure 8). The cushions consist of three layers of plastic with two air chambers between them that could be inflated or deflated as needed; the first layer is transparent; second and third layers have a reverse pattern that creates shade when inflated and joined together.

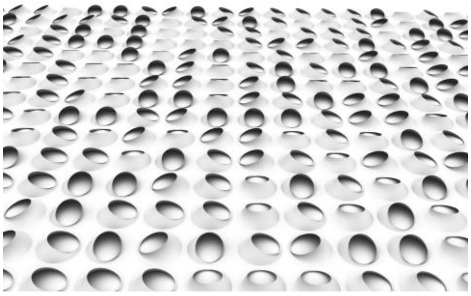

Figure 7. iConic, prototype of a dynamic building façade system designed my Matt Knapik , Eric and Mike Kryski from Laboratory for Integrative Design (LID), University of Calgary.

Figure 8. Media ICT building in Barcelona, by Enric Ruiz-Geli, features a dynamic facade made of "breathing" ETFE air cushions.

On the west side of the building, the ETFE air cushions are filled with nitrogen (mixed with tiny oil droplets) in the afternoon, transforming a transparent into a translucent façade that blocks 90% of the sun radiation, thus reducing substantially the building's heat gain. In addition, the building features a number of other control systems (based on over hundred networked Arduino boards) that can sense various changes in the environment and then produce a corresponding reaction not only in shading but also how the building is lit, etc.

Several researchers are looking into "organic" or biological paradigm of kinetic adaptation, which relies on material instead of mechanical actuation. Much of that work shares John Fraser's observation from his Evolutionary Architecture book, published in 1995, that "natural ecosystems have complex biological structures: they recycle their materials, permit change and adaptation, and make efficient use of ambient energy." For example, Achim Menges has recently designed HygroScope, a prototype that relies on intrinsic properties of material to produce an actuated response (figure 9). As described on his website (www.achimmenges.net), "the dimensional instability of wood in relation to moisture content is employed to construct a climate responsive architectural morphology. […] Mere fluctuations in relative humidity trigger the silent changes of material-innate movement." As Menges notes, "the material structure itself is the machine." Joanna Aizenberg at Wyss Institute at Harvard University has been experimenting with adaptive building materials, such as superhydrophic surface materials that can prevent or slow ice formation, can adapt from hydrophobic (non-wetting) to hydrophilic (wetting), and can collect rainwater efficiently; light-sensitive materials that control transparency and thermal gain; surface materials that can harness energy from the environment, etc. Other researchers are working with shape-memory materials, in which deformation can be induced (and recovered from) through temperature changes. Vera Parlac has experimented with shape-memory (SMA) alloys and Nick Pucket has used various shape-memory polymers to create material actuated prototypes of building facades.

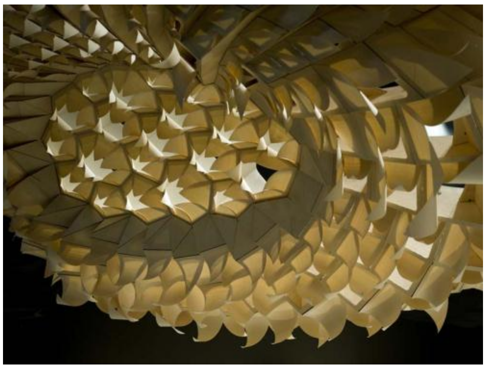

Figure 9. *HygroScope: Meteorosensitive Morphology* by Achim Menges, permanent collection, Centre Pompidou, Paris.

The so-called smart or designed materials that can change their shape based on external stimuli are of increasing interest to researchers in building industry. Besides shape-memory alloys and polymers that change shape based on temperature, there are magnetic shape alloys, in which magnetization affects shape, then photomechanical materials, in which light affects shape, electroactive polymers, pH-sensitive polymers, etc. Most of the prototypes that make use of these materials are small-scale; in fact, scale remains a principal challenge in developing such smart material-based systems, for the simple reason that materials behave differently, i.e. in non-linear manner, at different scales. So, what works at one-meter scale will not work at ten-meter scale. It is highly likely that most adaptive systems (at the scale of building) that rely on shape or volume changes in smart materials will be based on some kind of hybrid actuation, such as mechanic amplification of material-based actuation. For example, in the Hylozoic Ground installation, Phillip Beesley used mechanical levers to amplify contractions in “muscle” wire (i.e. shape memory alloy) used in the assembly that produce real-time dynamic behavior (figure 10). Such hybrid actuation, combined with proximity sensors and controlled through a network of Arduino microcontrollers, produced what looks like a living, breating forest of acrylic fronds that change shape as people move through the installation.

4. Towards Paskian Responsive Environments

The primary goal of constructing a truly responsive, adaptive architecture is to imbue buildings with the capacity to interact with the environment and their users. Architecture that echoes the work of Nicholas Negroponte could be understood as an adaptive, responsive machine—a sensory, actuated, performative assemblage of spatial and technical systems that creates an environment that stimulates and is, in turn, stimulated by users’ interactions and their behavior. Arguably, for any such system to be continually engaging, it has to be designed as inherently indeterminate in order to produce unpredictable outcomes. The user should have an effect on the system’s behavior or its outcome and, more importantly, on how that behavior or outcome is computed. That requires that both inputs and outputs of the systems be constructed on the fly. It is this capacity to construct inputs and outputs that distinguishes interactive from merely reactive systems.

Figure 10. Hylozoic Ground installation by Phillip Beesley.

The distinction between interactive and reactive is what enables adaptive, responsive architecture to be seen as an enabler of new relations between people and spaces. When Philip Beesley and his colleagues describe a responsive environment in Responsive Architectures: Subtle Technologies (2006) as a "networked structure that senses action within a field of attention and responds dynamically with programmed and designed logic," they are referring to what is essentially a reactive system. In contrast, Michael Fox and Miles Kemp (2009) argue that in "interactive" architecture, the interaction is circular—systems "interact" instead of just "react." The distinction between interaction and reaction (i.e., a system's response) is not clear-cut, because a dynamic action of a component, for example, could be seen not simply as a reaction but also part of the overall scenarios of interactivity. Tristan D'Estree Sterk (2006) distinguishes direct manipulation (deliberate control), automation (reflexive control), and hybridized models as forms of interaction between the users and the technologies behind responsive systems. For Sterk, "the hybridized model can also be used to produce responses that have adjustable response criteria, achieving this by using occupant interactions to build contextual models of the ways in which users occupy and manipulate space."

As Usman Haque (2007) puts it, the goal is "a model of interaction where an individual can directly adjust the way that a machine responds to him or her so that they can converge on a mutually agreeable nature of feedback: an architecture that learns from the inhabitant just as the inhabitant learns from the architecture." Thus, one of the principal challenges is how to construct (Paskian) systems that would provide enough variety to keep users engaged, while avoiding randomness, which could lead to disengagement if the output cannot be understood. The question: How does architecture avoid boredom and retain a high degree of novelty—another Paskian challenge. As observed by Haque, "unlike the efficiency-oriented pattern-optimization approach taken by many responsive environmental systems, an architecture built on Pask's system would continually encourage novelty and provoke conversational relationships with human participants."

There are other, more operational-based challenges that have to do with resolution of potential conflicts within systems. For example, Sterk discusses the coordination of responses at coincident, i.e. shared boundaries between spaces, as in a movable partition wall between two spaces, which can have actuators accessible by two independent control processes. Another issue is that while change is desirable, for most purposes, it would have to occur in predictable and easily anticipated ways. If that is not possible, then there ought to be a way (in certain circumstances) for users to preview changes before they are executed, or to choose among alternatives for one (perhaps suboptimal) that fits the current circumstances, needs, and/or desires. Users may need to be informed of the impact that selected changes would have on the environment or the shape and configuration of the space. The overall issue of control is critical. In Smart Architecture, Ed van Hinte (2003) warns that "sometimes a simple and hence ostensibly 'dumb' building is smarter than a technology-dominated living-and-working machine over which the user has lost control."

When it comes to designing adaptive, responsive environments, the "software" side does not seem to present as many challenges as the "hardware" side, the building itself, whose majority of systems are inherently inflexible. That is perhaps where the biggest challenges and opportunities exist, as buildings would have to be conceptually completely rethought in order to enable them to adapt (i.e., to reconfigure themselves). Then there is the "middleware" that sits among the software and hardware and the users as devices that facilitate the feedback loops between the components of the system.

There are also some fundamental questions that have yet to be adequately addressed. For example, while Beesley and his colleagues (2006) predict, "the next generation of architecture will be able to sense, change and transform itself," they fail to say clearly towards what ends. Even though they ask what very well may be the key question—how do responsive systems affect us?—they do not attempt to answer it explicitly. Similarly, Fox and Kemp (2009), in their Interactive Architecture book, avoid explaining fully—and admit as much—why interactive systems are necessary, meaningful, or useful, and simply state, "the motivation to make these systems is found in the desire to create spaces and objects that can meet changing needs with respect to evolving individual, social, and environmental demands." Fox and Kemp position interactive architecture "as a transitional phenomenon with respect to a movement from a mechanical paradigm to a biological paradigm," which, as they explain, "requires not just pragmatic and performance-based technological understandings, but awareness of aesthetic, conceptual and philosophical issues relating to humans and the global environment."

5. Towards Architecture Of Change

"Accepting the dynamics of buildings and cities…can turn architectural change into an ecologically efficient process as well as a new urban experience."
—Ed van Hinte, et al., *Smart Architecture*

The quest for an architecture of change is a reflection of the context in which we live and work. An ever-increasing pace of change is what defines contemporary life: socio-economic, political, cultural, and, in particular, technological context are constantly shifting, altering the norms, customs, and expectations and affecting how we use and relate to space. A rapidly changing socio-economic, cultural, and technological environment demands buildings that can adapt quickly. How buildings can adapt and how they respond to change depends on the nature of change (i.e., on the context in which the change occurs [programmatic use, building systems, etc.]).

In Flexible: Architecture that Responds to Change, Robert Kronenburg (2007) argues that for a building to be “flexible,” it must be capable of (1) adaptation, as a way to better respond to various functions, uses, and requirements; (2) transformation, defined as alterations of the shape, volume, form, or appearance; (3) movability; and (4) interaction, which applies to both the inside and the outside of a building. Such capacities in buildings will be provided by “intelligent” building systems, which will be driven by many factors, from environmental ones, such as the control of energy use, to changing the appearance of the building through varying images and patterns. The systems could be either automatic or “intuitive,” suggesting a capacity of the system to infer from the context an appropriate set of responses without overly explicit inputs.

In a quest to establish a context for change and variety in architecture, an international network for so-called Open Building (www.open-building.org) was established early in this decade. In Open Building, the focus is on disentangling building systems and subsystems from each other so that they can be better organized to facilitate not only their efficient assembly, but also their disassembly and reassembly in different configurations. Open Building separates the major systems into the building site, structural envelope, division of space inside the building, plumbing, wiring, heating/cooling, and the cabinets, furniture, and “other stuff that people put inside the building.” One of the main distinctions that Open Building makes is between “support” and “infill,” where “support” refers to the structural envelope, and “infill” to all the other systems that are housed within the envelope. Without referencing the Open Building movement, Tristan d’Estree Sterk also separates the components of buildings into two main classes of parts: the serviced spaces (responsive, internal partition systems) and the external shells (responsive building envelopes or structures). Thus, building design becomes two-level: first, the overall structural envelope is designed, and then the infill. Critical to successful implementation are interfaces between different systems, which should be designed to allow different choices of systems and their replacement, as in different fit-out systems applied in each unit, depending on the choices made by the users.

While Open Building as a design and building method aims to address the changing social and technical context in which we live and work, it focuses on building systems as a technological enabler for effective changes in use (i.e., adaptive re-use). It recognizes that there are distinct levels of intervention in the built environment; that users may make design decisions, as well; that design is a process that involves many different disciplines and professionals; and that the built environment is in constant transformation (i.e., subject to continuous change) and is the product of a never-ending, ongoing design process in which it is transformed part by part.

Ed van Hinte and the other authors of Smart Architecture (2003) also articulate a need for architecture to develop ways of designing buildings that can change, but do so with a dimension of time explicitly in mind. According to them, buildings could be divided into seven system-based layers, each with its own lifespan that ranges from centuries, down to a couple of years. The layers are (in ascending order, depending on life span): location, structure, access, façade, services, dividing elements, and furniture. They warn that the dynamics of these layers—and their different life spans—have to be taken into consideration when designing “integrated” buildings. (A building with tightly integrated building systems may not have a capacity for change if the systems are impossible to separate and disassemble.)

If we were to accept change as a fundamental contextual condition—and time as an essential design dimension—architecture could then begin to truly mediate between the built environment and the people who occupy it. As Ed van Hinte and his colleagues note, "instead of being merely the producer of a unique three-dimensional product, architects should see themselves as programmers of a process of spatial change." The principal task for architects is to create "a field of change and modification" that would generate possibilities instead of fixed conditions. The inhabitable space would then become an indeterminate design environment, subject to continuous processes of change, occurring in different realms and at various time scales:

It is the form that is no longer stable, that is ready to accept change. Its temporary state is determined by the circumstances of the moment on the basis of an activated process and in-built intelligence and potential for change. Not product architecture then, but a process-based architecture whose form is defined by its users' dynamic behaviour and changing demands and by the changing external and internal conditions; an architecture that itself has the characteristics of an ecological system, that emulates nature instead of protecting it and therefore engages in a enduring fusion of nature and culture.

As Ed van Hinte and his colleagues point out, "that would be a truly ground-breaking ecological architecture." But to get there, we need to first answer some fundamental questions pertaining to change as a conceptual and time as a phenomenological dimension in architecture. We need to go beyond the current fascination with mechatronics and explore what change means in architecture and how it is manifested: buildings weather, programs change, envelopes adapt, interiors are reconfigured, systems replaced. We need to explore the kinds of changes that buildings should undergo and the scale and speed at which they occur. We need to examine which changes are necessary, useful, desirable, possible… The principal argument is that change in architecture is far from being adequately addressed or explored theoretically, experimentally, or phenomenologically; much remains to be done.

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