Material Agency and Physical Boundaries

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The research builds on the relationship between matter and energy and the idea of boundaries as sentient interfaces capable of affecting our bodily experience and perception of space due to their inherent physical attributes. Two key issues addressed are firstly, the revisiting of the architectural boundary as a thermodynamic zone and secondly, the identification of material behaviour in relation to energy stimuli. It is argued that the transient behaviour of materials can offer an instrumental reconsideration on how architecture establishes spatial articulation through boundaries and this is demonstrated through a design-led project.

Keywords: thermal field, responsive materials, passively active materials, heat transfer, thermodynamic, matter and energy

INTRODUCTION: MATERIALITY IN ARCHITECTURE
As architects one of our basic tools for organising space is by constructing and distributing boundaries, defined by facades, doors, walls, and floors among others. Those boundaries control, converge and disseminate activities within an enclosed defined space that separates the inside from the outside. On the other hand, the boundary for physicists is a dynamic element, a transitional zone between matter and energy, which remains changeable over time (Addington and Schodek 2005).

According to Michelle Addington (2010), geometry is privileged in architecture due to "an a priori belief that perception is rooted in geometry". As a consequence of that, the materiality of architecture becomes an "aesthetic artefact" rather than an "instrumental" agent intertwined with energy qualities.

Indeed, both the concept of Aristotelian hylo-morphism -morphing of matter- and Plato's theory on the purity of form are long-standing believes in architecture (Thomas 2007). In this binary relation matter becomes a passive agent on which form is being imposed.

Since the Renaissance and most recently in Modernism, architectural elements were conceived as pure, texture less and geometrically recognisable objects. This perception has not changed a lot with the advent of postmodernism and the current more expressive architectural formations.

The introduction and utilisation of technology -such as the heating and air-conditioning systems- resulted in a consequent separation between building performance and building morphology while amplifying architectural "discreteness" (Hensel 2013).

A primary assumption that this paper is making is that any construct is not only the visible static form, but also the invisible heterogeneous space that it conveys through matter-energy relationship. The choice of materials in relation to the environment becomes an important task for the creation and modulation of spatial characteristics informed by differ-
ences of light, temperature, sound and humidity.

RESPONSIVE ARCHITECTURE
In the current era, human, technology and nature are fused together by exchanging information. The pureness of each one is not discernible. The post-human approach extends the notion of the body to cyborg, the notion of nature to techno-nature and the notion of materiality to meta-materiality.

This is similarly evident in architecture, where the use of smart materials, ubiquitous systems and technological machines, "challenges the long-standing conception of the building as an object autonomous from its environment and governed by disciplinary interiority" (Harisson 2013).

The desire for a responsive architecture capable of transforming, interacting and communicating with the environment and its users is evident in different periods of time within architecture, influenced by systems theory and cybernetics. The architecture of that period - mainly during the 60s - has been prone to new materialism, which acknowledged the "diversity and untidiness of the world as well as the social and psychological experience" (Sadler 2005). Architects have designed and prototyped the essence of an altering architecture by integrating electronics, computers and circuits in architectural components.

Through the investigations of the past and the present it is often evident that material inertia has caused a problem in realising dynamic, living architecture. Advancement in material science and engineering paves the path towards conceptualising architectural projects, which are open to communication with their physical environment.

RESPONSIVE MATERIALITY
Materials with computational logics, referred to as smart, responsive, or active, are composite materials where bits (computation) and atoms (materiality) meet (Ishii 2012) and which can easily change between two or more states. They are mainly engineered materials whose properties are defined in labs, expanding the range of interaction that is possible with natural ones.

They can be distinguished in two broad categories: 1) those that change their properties in response to external stimuli, and 2) those that provide energy transformation functions. In the first category, materials have intrinsic response to specific stimuli, while in the second the response can be computationally controlled or enhanced (Addington and Schodek 2005). Additionally, 3) a third category includes passive materials that without themselves undergoing change, they display different effects under altered environmental conditions, i.e. dichroic films and fibre optics.

Attributes of responsive materials
With the aim of familiarising with their behaviour, limitation and potentials, a series of testing was initiated on readily obtainable responsive materials (Figure 1).

This change from one state to another can reveal the presence and concentration of various substances which are not otherwise perceptible. For example photochromic materials illustrate change of light intensities, thermochromic demonstrate change in temperature gradients, hydrogels can expand in response to humidity levels or even to pollution levels, and shape memory polymers change shape in response to temperature or electricity.

These connections can be customised according to different needs and wills. Especially nowadays that data sensor networks are proliferating, the connection between materiality and urban environmental data is becoming more crucial. Responsive materials thus, can acquire a profound role on raising awareness on environmental conditions by visualising invisible environmental agents.

Furthermore, this change of state can become a mediator of passive microclimatic adaptation. Examples include the altering optical characteristics of thermochromic materials which not only exhibit temperature differences, but also have the potential of enhancing thermal regulation due to the absorption or reflectivity of particular colours (Figure 2). For
Small-scale models of different responsive materials such as photochromic that change with light intensity, thermochromic applied on wood and fabric, phosphorescent, shape memory polymers, hydrogel in latex and liquid crystal thermochromic.

Models based on thermochromic ink mixed with plaster (a,b,c) or silicon (d). The colour changes either due to directed hot air (a,b,d) or warm water passing inside model (c).

Figure 1

Figure 2

Similar propositions have been made in the past but have not yet been developed or applied further. The Cloudgel, a thermo-chemical device introduced by Day Chahroudi is based on chemical adaptation on a molecular level. The main material, sandwiched between two glass panels, changed from transparent when temperature was low to white when the temperature increased and it described "an autonomous solar powered temperature control system" (Davies 1981).

Ultimately, a remarkable feature that responsive materials have is that they behave similar to biological systems: they are inseparable from the energies they convey, the energies that change their state and the energies they absorb and emit. They eventually, configure autopoietic systems, which are open to information, while their organisation remains closed, and they do so through their one material make-up and without being comprised by discrete mechanical elements (Doumpioti et al. 2010).

Material limitations and potentialities

At their current form however, available responsive materials exhibit the cause-and-effect behaviour
Passively Active Materials and Physical Boundaries

While the initial aim of the research focused on the potential utilisation of smart materials in architecture, their transient behaviour has furthermore contributed to new insights on materiality not necessarily bound to dynamic response but to the capabilities of all materials to be active even when no change is noticeable. Any material construct is not only the visible static form, but also the invisible heterogeneous space that it conveys through matter-energy relationship.

In relation to this, architect Usman Haque makes a distinction between the hardware and software of architecture, where the walls, roofs and floors are the static elements that define the hardware of architecture, and the sounds, smells, temperatures, radio waves are the ephemeral elements that define the software (Haque 2004).

All architectural elements are dynamic in the way their material make up mediates energies and although they do not move or change position, they are concurrently active since their behaviour results "in the creation of qualities the world lacks... seemingly at rest, they are secretly at work" (Leatherbarrow 2009).

Vernacular architecture and the distinction between logical, physical and sensorial boundaries

From simple systems to more elaborated ones, vernacular architectures around the world serve as profound examples on the relationship between (passive) materials and climatic energies. Their geometry, materials, openings and orientation are strategically articulated for environmental mediation.

One such example, the Ondol, developed at about 1,000 BCE was a radiant heating floor for the traditional Korean house, the Hanok. The hot air originating from the kitchen fireplace placed at the exterior of the house was channelled through cavities to the under floor area and finally it was exhausted through a chimney. Cavities were shaped by either clay or bricks and were covered by large slabs of stone. The clay helped in sealing the combustion gases from penetrating the living space, while the stone slabs were becoming warmer by absorbing heat and radiating it above (Figure 3).

Besides its functionality as a thermal system, the Ondol stimulated the creation of social patterns with the "eldest occupying the warmest zones of the floor" (Moe 2010).

The under floor heating system has been utilised extensively in vernacular architecture spanning from the Roman hypocaust, to the Chinese Kang, and the Spanish Floria, to name a few. Currently, the technology is becoming popular again with the development of under floor heating system based on water or electricity. What distinguishes the vernacular sys-
tem though, is the synergetic relationship between different elements in order to achieve adequate interior thermal quality. All, structure, materials, geometry, and other design decisions are interrelated aspects of the overall system.

The boundaries described by vernacular architecture are physical boundaries as opposed to logical or “discrete” ones (Hensel 2013). While the logical boundary is an entity of visual demarcation and spatial articulation delineated in static formations, the physical boundary describes a zone of fluctuations that emanate from the interaction of the material surface and the energies that surround it. In the first instance, form is untainted by matter and matter is subordinated to form. In the second, matter and energy animate architecture and become perceptible from all our senses.

CASE STUDY: THERMAL FIELD, PASSIVE AND ACTIVE MATERIAL ENERGY TRANSFORMATIONS

The thermal field project is a study on radiant surfaces, similar to the Korean Ondol described above. The research initiated by experimenting with thermochromic materials and evolved into the idea of an interactive version of a radiant thermal surface comprised by passive and responsive materials by considering their distinct yet complementary attributes.

Similar to Raynar Banham’s (1984) renowned parable of the fire as a source of spatial differentiation, the project aims at the creation of a thermodynamic field as a space of social interaction in urban settings. It aims at acting as a mediator between the users and the existing microclimate by altering the temperature differences according to their preference and creating emergent climatic patterns.

While climatic control and regulation is most often associated with building interiors, the project aspires to its extension to exterior environments for the amplification of public activities and social interaction.

Although, as described earlier, heat transfer and thermal modulation played an important role in the past, there are only scarce examples in contemporary architecture. Two profound representatives of this field are Sean Lally (2009) and Philippe Rahm, who foster through their ideas new relationships between urban space and climate and propose through their projects, activities -augmented by heat- that might otherwise be assumed to need a conditioned interior.

Interface Components

The interface of the thermal field consists of a distribution of small heat sources (peltier units) activated by microcontrollers (arduinos). These devices can cool down or heat up depending on the direction of the current running through them. When the thermoelectric units are activated their heat is transmitted through a highly conductive material (copper sheets) to the upper ceramic surface, which is treated with thermochromic ink (Figure 4).

The connection between matter and energy alters according to the local materiality, ranging from energy transfer (thermoelectric units and heat conductive tiles) to phenotypical change (thermochromic materials) and to energy exchange...
(through conduction, convection, radiation) between the surface, the environment and the users. While at this stage the microcontrollers are pre-programmed, the aim is for the system to be locally defined by the users who, through their devices, can select the range of temperature transferred to the tiles and consequently conducted to their own body.

While thermal conductivity refers to the ability of the material to transfer heat, the specific heat property indicates how much thermal energy a material can hold in its molecular structure for a given mass. Different combinations of materials were tested and placed in relation to their role within the system. The peltier units were positioned within wooden frameworks, and star-shaped copper sheets were placed on top, as copper is highly conductive. Tiles made of different material combinations then absorbed the heat transferred by the copper sheets. The tiles were made by a) liquid crystal sheet b) plaster, c) fibre composite plaster or, d) plaster with Phase Changing Material (PCM), testing their heat transfer behaviour. The latter is a material with unique phase changing properties as it can change from solid to liquid and vice versa according to temperature differences, and acts as a temperature buffer.

The material combinations and consequently the thermodynamic behaviour of the overall surface can thus, vary extensively (Figure 6).

Contribution and Further Development of Thermal Field
Within a conceptual frame, the dual aim of the project is firstly to stimulate an interrogation of the purely formal perception of the architectural boundary to a dynamic and sentient one and contribute to a field of knowledge that sees architecture beyond its static limitations towards one that is energy-related. In this sense the project aspires to combine the atmospheric with the performative qualities of the matter-energy relationship.

Further development will focus on the following aspects: the first is the connectivity between user and interface and furthermore the heat transfer at-

**Thermal Behaviour**
Due to its heat-sensitive qualities the interface becomes a data visualisation apparatus, revealing information and affecting modes of occupancy (Figure 5).

The thermal behaviour of the interface—how fast it gets heated, for how long and on which location—is always indicated visually by the emerging patterns caused by the thermochromic ink. The physical properties of the upper stratum are crucial in relation to the thermodynamic behaviour of the system. Their behaviour can be programmed in their material properties and by altering two main attributes: heat conductivity and specific heat.

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tributes of the surface in relation to its materiality and geometry. The latter is an investigation on how geometry and spatial qualities affect heat transfer and distribution. Finally, an additional aim is to rethink the current energy consumption of the interface with the utilisation of distributed energy harvesting devices capable of converting ambient energy to electricity.

Figure 6
Some variables that affect the interface's performance, from top to bottom: a) Difference of internal material conductivity. The star-shaped copper transmits heat. b) Difference of external material conductivity and heat capacity: liquid crystal surface vs plaster, c) difference of internal temperature from thermoelectric device.

CONCLUSION
Thinking with responsive materials poses some intriguing questions to architecture. Are we to continue designing similar forms with new materials or is it time to generate new connections between matter and form? Moreover, have we exploited the potentialities stemming from traditional materials and their distinct properties in relation to acoustic, luminous and thermal energies? How can matter and energy define the formal aspects of architecture?

The paper poses a twofold observation: firstly is that responsive materials can pave the path for new connections between the static built form and surrounding dynamic events. The steps taken by fields like material science and bioengineering make us envision a future reality where materials play a key role in defining highly dynamic and responsive environments. Materials that grow and self-organise by having integrated processing capacities may lead to unseen possibilities on spatiality by overcoming the static and pre-determined qualities of the existing.

The second remark is that despite the utilisation of responsive materials, architecture would profit by reconsidering the attributes of traditional materials and integrate their 'passively active' behaviour. The make up of materials at a micro-scale as well as their organisation and assembly at a larger scale can yield highly heterogeneous thermal or acoustic and luminous spatial environments. Likewise the notion of the boundary can shift to something that is dynamic and closer to the physicists' idea of an ever-changing one.

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