Adaptive Architecture – A Conceptual Framework

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Abstract

Adaptive Architecture is a multi-disciplinary field concerned with buildings that are designed to adapt to their environments, their inhabitants and objects as well as those buildings that are entirely driven by internal data. Because of its multi-disciplinary nature, developments across Architecture, Computer Science, the Social Sciences, Urban Planning and the Arts can appear disjointed. This paper aims to allow readers to take a step back advancing the exploration of thematic and historical links across this exciting, emerging field. To this aim, it presents a cross-disciplinary framework of Adaptive Architecture, discussing motivations for creating Adaptive Architecture, before introducing the key interlinked components that creators draw on to create adaptiveness in buildings. This is followed by a brief outline of overarching strategies that can be employed in this context.

Introduction

Adaptive Architecture is concerned with buildings that are designed to adapt to their environments, their inhabitants and objects as well as those buildings that are entirely driven by internal data. The term is an attempt to incorporate what people imply when they talk about flexible, interactive, responsive or indeed media architecture, the mounting interest in this emerging field being demonstrated by the large variety of recent publications, (Kronenburg, 2007) (Harper, 2003) (Streitz et al., 1999).

Overall, Adaptive Architecture is not a well defined field of architectural investigation. It ranges from designs for media facades to eco buildings, from responsive art installations to stage design and from artificial intelligence to ubiquitous computing, just to mention a few examples (Tscherteu, 2009, Roaf et al., 2007) (Bullivant, 2005) (Eng et al., 2003) (Rogers, 2006). As will be clear to anyone attending this conference, Adaptive Architecture brings together a number of different concerns stemming from a wide variety of disciplines, spanning Architecture, the Arts, Computer Science and Engineering among others. Whether buildings in this context are described as flexible, interactive or dynamic, they embrace the notion of Architecture being adaptive rather then being a static artefact, often with an emphasis on computer supported adaptation.

This multi-disciplinarity has great advantages when the latest developments in different areas converge to create exciting new designs, experiences and lived-in buildings. It can also make the emerging field of Adaptive Architecture appear overly complex and disjointed. This might lead to the same ideas being constantly recycled without reference to precedent because it 'hides' in a different discipline. This becomes a problem, when the same mistakes are repeated. This paper will not solve this problem, but it aims to contribute to a better understanding of developments in Adaptive Architecture across its component disciplines. For this, a more conceptual view of the field is required that demonstrates thematic and historical linkages across the entire area.

This conference contribution has the simple aim to explore the burgeoning field in a rigorously structured fashion categorising the key elements of adaptive buildings, regardless of where they are employed, from Plug in City to Eco Houses(Price, 2003) (Willmert, 2001). With this aim in mind, the paper does not revolve around case studies and a description of their properties. Instead it focuses on common properties of Adaptive Architecture, which are then illustrated with case studies. This is done by proposing a structure for discussion and categorisation, which will be introduced below. In what follows, the term 'Adaptive Architecture' will be defined, before introducing the framework itself. This will be followed by a brief discussion of common design strategies that architects have access to when designing for adaptiveness.

Definition of Adaptive Architecture

All Architecture is adaptable on some level, as buildings can always be adapted 'manually' in some way. Brand's 'How Buildings learn' provides an insight into the different levels of adaptation to be expected and how these apply over different time scales (Brand, 1994). The use of the term 'Adaptive Architecture' must therefore be seen in this overall context and the following delineates between adaptable and adaptive: Adaptive Architecture is concerned with buildings that are specifically designed to adapt (to their environment, to their inhabitants, to objects within them) whether this is automatically or through human intervention. This can occur on multiple levels and frequently involves digital technology (sensors, actuators, controllers, communication technologies). Taking the above context into account, this definition and associated framework is therefore an attempt to incorporate a variety of approaches, such as those labelled flexible, interactive, responsive, smart, intelligent, cooperative, media, hybrid and mixed reality architecture (Kronenburg, 2007, Bullivant, 2005, Harper, 2003, Streitz et al., 1999, Zellner, 1999, Schnädelbach et al., 2007). All the above come with their own connotations and particular areas of focus. Adaptive Architecture as it is presented here, is structured to be independent of any of these particular concerns.

Before continuing with the body of the paper it is worth to set out one additional delineation. Although the term Adaptive Architecture is often used there, design processes themselves that are computationally adaptive to data drawn from the environment, inhabitants or relevant objects are not included in the framework. Recent approaches in generative design methods and data driven architecture highlight such adaptiveness during the design process. However, these do not necessarily in themselves lead to buildings that are adaptive during their occupied life cycle. However, they certainly do present a fascinating research field in themselves.

The framework

The framework itself is structured along the following categories. It begins with motivations and drivers, asking the fundamentally important question for the reasons of the construction of Adaptive Architecture. This is followed by a series of more practice-related categories detailing components of adaptive buildings. The framework steps through what adaptive buildings react to, what elements in adaptive architecture are adapted, the method for adaptation and what effect adaptations have.

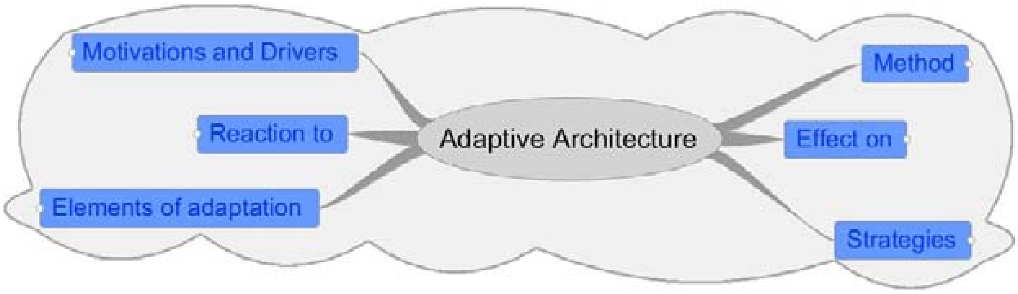

Figure 1 Top level framework categories

The framework concludes with a discussion of overall strategies which look to incorporate multiple tactics drawn from the various adaptation components in overall strategies. Please compare Figure 1. The above categories are carefully illustrated through built cases, design prototypes and the literature. However, this framework does not attempt to be exhaustive in the way it makes use of examples. The aim is not to list all possible examples but to list those which illustrate the particular category well. When appropriate, the same example can appear in multiple categories for this reason. The emphasis is on allowing the reader to step back, explore links, make connections and understand historical dimensions of Adaptive Architecture in a structured way.

Motivations and Drivers

Motivations and drivers for designing for adaptiveness are numerous and varied. They can lie in cultural, societal and organisational domains as well as being concerned with communication and social interaction.

Cultural

Adaptive spaces for cultural production have clearly a extended design history. Theatre spaces and concert halls have long incorporated technologies that allow them to adapt to different events and there is a complex range or technologies available that allows this to happen. There are other culturally focussed spaces that adapt to various parameters. For example, Adaptive spaces are being created with the sole aim to explore or demonstrate a particular scientific debate. The SPECS group at UPF Barcelona creates what they term 'inside-out-robots', inhabitable experimental spaces that are designed to allow researchers an exploration of how the human mind works [SPECS, Synthetic Oracle, Barcelona, Spain, 2008] . In a similar vain, adaptive spaces are set up to demonstrate a particular issue through artistic and architectural exploration and investigation, examples of this process being exhibited at CITA Copenhagen. Here the intricate relationships between tangible physical materials and intangible digital data are exposed through room-sized robotic membranes [CITA, Vivisection, Charlottenberg Art Museum, Copenhagen, Denmark, 2006]. A different direction is taken by cultural architecture that focuses on education. Recently, there has been a lot of attention on learning environments and the InQbate space at Sussex University is an interesting case in point. It combines rotatable partitions, curtains and flexible seating with a high-tech layer of digital technologies to allow flexible projections and audio productions for example [Sussex University, InQbate, Brighton, UK, 2007].

Societal

One of the most prominent societal reasons for the design for adaptiveness is life style. Traditional Japanese domestic architecture responds to spatial constraints by producing highly adaptive interiors, a strategy taken on board by early modernists. Rietveld's Schröder house offers sliding and folding partitions to allow inhabitants to adapt the space to their needs [Rietveld, Schröder House, Utrecht, The Netherlands, 1924]. Nomadic life-styles, whether traditional or modern, lead to buildings that are transportable but also often re-configurable. For example, Horden's iconic Skihaus was a structure that could be airlifted to a mountain side to provide shelter [Richard Horden, Skihaus, Switzerland, 1990-2005]. Clearly, the drive for environmental sustainability is a key driver at present and buildings are designed to adapt with the aim to lower the resulting CO2 emissions in particular. There are many examples of such buildings, but the need for further research is demonstrated by the recent extension of a research programme making use of fully instrumented EcoHouses [Derek Trowell Architects, The BASF House, 2008, University of Nottingham, UK]. Another somewhat more mundane motivation is architectural fashion. Architectural designs follow fashion but also technological trends to some extent and individuals and organisations are interested in being part of a particular trend, or at the very least not to appear entirely outdated. Architecture can be designed to be responsive to such adaptations by providing a flexible framework that allows relatively rapid updates.

Organisational

The third category of motivations can be described as organisational. Adaptive buildings are designed to deal with changing circumstances. The occupation of buildings changes at different time scales: there is rapid change through different activities throughout a single day, medium term change as result of re-organisations and longer term changes that might impact not only the building itself but also its surroundings. Some times the need to respond to different time scales finds a direct implementation as with the Pompidou Centre, where partitions have different levels of flexibility depending on their purpose [Rogers & Piano, Centre Pompidou, Paris, France, 1977]. The above applies to different occupant categories from family units to large corporations and finds expression in projects of the related scales from Steven Holl's Fukuoka Housing project [Steven Holl, Fukuoka Housing, Fukuoka, Japan, 1991] to Grimshaw's Igus factory [Nicholas Grimshaw, Igus factory, Cologne, Germany, 1999-2001]. In addition to changes in occupation, buildings are also designed to cope with changes in their environments. In the most extreme case a site becomes unsuitable and a portable building can then be re-located. It might also be that a design attempts to anticipate more subtle environmental changes, such as those caused by climate change. Certainly larger organisations have then also been motivated by a drive to operate buildings more efficiently, and this has given rise to the relatively early introduction of electronic building management systems into corporate architecture roughly in the 1970's. More recently this has started to overlap with the societal motivation to operate buildings in a more environmentally sustainable way (see related section above). Modern office buildings frequently combine efficient design and operation with sustainability aims. The University of Nottingham's Jubilee Campus developed is an interesting example combining relatively low-tech construction with a sophisticated set of building management tools [Michael Hopkins, Jubilee Campus, Nottingham, UK, 1999]. The final organisational motivation can be summarised as flow management. Buildings are designed to cope with varying flows of people triggered by for example time of day (different flows during rush hours), emergency situations (allowing supporters on to the football pitch in certain circumstances) and variations in activity. Such flexible management is routinely done at large traffic exchanges and Foreign Office Architect's Yokohama ferry terminal provides a good example. Its large open plan areas can be re-configured to allow different streams of passengers, to separate national from international departures for example [Foreign Office Architects, Yokohama Ferry Terminal, Yokohama, Japan, 2002].

Communication

The final motivation and driver identified here is concerned with communication. There are buildings that are designed to be adaptive so that they better support different episodes of social interaction. In physical space, this can be achieved through changing layouts to manage the location of individuals in physical space, for example by re-arranging seating layouts as seen at the Toronto Skydome [Robie & Allan, Toronto Skydome, Toronto, Canada, 1988]. It is also related to flow management, highlighted when the interaction between certain streams of people is prevented for example in airport or court house design. There are also digital ways to adapt buildings with the aim to enhance social communication. Conferencing technologies, embedded into physical architectural design is designed to bridge between multiple physical sites, in particular with a view to reduce the need for travel [HP, Halo Telepresence System, Multiple Sites, 2007-

2010]. With the aim to support informal and spontaneous communication between multiple office locations, hybrid spatial topologies introduce virtually dynamic spatial relationships into the built environment [Schnädelbach, Mixed Reality Architecture, Multiple Sites, 2003-2010]. Less focussed on social interaction but instead concentrating on getting across a message are those buildings that quite literally carry the corporate image of an organisation. The rapidly developing area of media-façades is the most direct example of this and the new Munich football arena a good case in point. Its façade changes colour depending on which team plays the stadium [Herzog & de Meuron, Allianz Arena, Munich-Germany, 2005]. Beyond displaying a message, those approaches can also be used to engage with a potential customer basis. Dytham's iFly Virgin Wonderwall is an early example of such a strategy, allowing passers-by to interact with the façade via their mobile phones. [Klein Dytham Architecture, iFly Virgin Wonderwall, Tokyo, Japan, 2000].

The Adaptive Building and it Components

For whatever reasons adaptive buildings are designed, constructed and occupied, they have a number of fundamental elements that re-occur across the design space that makes up Adaptive Architecture. These elements will be discussed in what follows. The first category is concerned with in reaction to what building are designed to be adaptive, which is followed by a discussion of the elements that can be made to adapt. The methods of adaptations will be introduced before outlining some of the possible effects. Where possible, each of the categories will be illustrated through a relevant example.

In reaction to what? - Logical data source driving adaptations

In reaction to what is Architecture designed to be adaptive? Three main categories can be identified. Adaptive Architecture responds to inhabitants, the environment and objects, and those will be considered in turn.

Inhabitants

Architects might focus their design efforts on individual inhabitants of an adaptive building. Individuals might then be empowered to change architectural layout manually or the building might respond to them in a particular way automatically, for example drawing on personal data that might be available to the building about them. Bill Gates residence is a well known exemplar case in this context, where a body worn personal tag is able to identify individuals and adjust temperature, music and lighting accordingly [James Cutler Architect's & Bohlin Cywinski Jackson, Bill Gates' House, Medina, Washington, USA]. Most buildings are not just occupied by a single individual however. Designing for adaptiveness for groups of individuals can be a real challenge in turn. Once again an architect might concentrate on providing the possibilities for manual adaptations. Those will then be negotiated amongst inhabitants. The automatic adaptation of buildings towards groups of individuals entails knowing something about their group behaviour, probably learning over time and building up the necessary profiles. Technically, the complexity lies in aggregating from multiple streams of personal data and finding a way to aggregate those streams in a way that is meaningful and useful. The Adaptive House at the University of Colorado explored that space by taking in data from multiple inhabitants to allow the house to adapt a variety of parameters [Mozer, The Adaptive House, Boulder, USA, 1997]. Finally, organisations with organisation-wide motivations and strategies are a group of inhabitants that design for adaptiveness has to address. Organisational structures include those parts that manage the building facility overall, those parts that operate facilities on a daily basis (frequently 3rd party organisations) and the actual occupying organisation, which might well be different from both the above. Adaptiveness needs to address their concerns with regards to keeping facilities responsive to organisational changes but also manageable on a day-to-day basis.

Environment

Adaptive Architecture can be designed to react to its exterior environment. As already highlighted, it is the societal motivation to live more sustainably that is a key driver in Adaptive Architecture at present. Adaptive elements are also designed to react to the interior environment, for example to ensure that temperatures inside are comfortable for inhabitants, but also to control the energy expenditure in achieving a particular comfort level. The previously introduced University of Nottingham research building does both as many technologically driven eco-projects would [Derek Trowell Architects, The BASF House, 2008, University of Nottingham, UK].

Objects

Adaptiveness in reaction to objects is comparatively much less common or at least less discussed. Buildings can be thought of that react to objects passing through. For example, a building might automatically restrict access to specific category of people when a specific, may be a particularly valuable, object is present. In a similar way, a warehouse might prepare the correct loading bay in anticipation of a particular delivery coming in. Objects within buildings can also play a more direct role in the process of adaptiveness in buildings. For example at the InQbate learning environment, a tangible interface object based on a colour-coded cube allows the mixing of ambient colour in the overall space [Sussex University, InQbate, Sussex University, UK, 2007]. Finally, one might also think about adaptive architecture that adapts to objects passing by or overhead. Work within the Curious Home project at Goldsmith's college has explored a domestic device that visualises the passing air traffic to give people living in the flight path near busy airport a handle on what goes on over their heads [Interaction Research Studio, Goldsmiths College, The Plane Tracker (The Curious Home), 2007]. Extending this idea, taking similar data streams, one could think of buildings that for example change their acoustic properties, when objects are passing that produce unwanted noise.

Elements of adaptation

Within each adaptive building there are a number of elements that can be adapted. Elements of adaptation take a central role in Adaptive Architecture. Their selection is driven by the original motivations and by what adaptive buildings react to. They directly impact on the effect that is generated within an Adaptive Building (see below). The following steps through descriptions of the following elements of adaptations: surfaces, components and modules, spatial features and technical systems.

Surfaces

External and internal surfaces can be made to adapt. External adaptive surfaces are typically facades. Fundamentally there are two forms of adaptations. Mechanical adaptations change the appearance and overall properties of an architectural surface by mechanically altering its components. The Institut du Monde Arabe in Paris has demonstrated the maintenance difficulties that such technical complexity brings to the fore [Jean Nouvel, Institut du Monde Arabe, Paris, France, 1989]. Lighting and display technologies offer the second technical way for adapting surface elements. Such technologies are the original core of media façade work and there are many existing examples. Cook and Fourier's Kunsthaus embeds individually addressable lights into its façade that can be combined for graphical effects and to display text [Peter Cook and Colin Fourier, Kunsthaus Graz (BIX), Graz, Austria, 2005]. Internal surfaces are also frequently adapted to different needs. Often this is for information visualisation. Very commonly, digital image projection transforms architectural surfaces into information displays. There are also dedicated efforts to make more surfaces 'writeable-on'. InQbate, the learning space at Sussex University already mentioned combines both of these strategies [Sussex University, InQbate, Sussex University, UK, 2007]. Another type of surface adaptation is concerned with making decorative changes and through that influencing the ambiance of a room. Winfield's Blumen Wallpaper is an interesting example as it adapts its lighting patterns and through those changes the appearance of the wall surface [Rachel Wingfield, Blumen Wallpaper, 2004].

Components and modules

The next sub-catebory is focussing on components and modules. Components can be re-used, i.e. building construction that is focussed on re-using existing components such as the work by Santiago Cirugeda [Santiago Cirugeda, Urban Prescriptions, Barcelona, Spain 2005]. Components can clearly also be specifically designed to increase adaptiveness. Weatherheavens Series 4 portable shelter is designed around such a strategy for example [Weatherheaven Resources Ltd., Series 4, (Product), 2010]. There are also internal adaptive elements that do not require the replacement of any one component. Adaptive internal partitions are possibly one of the most common adaptive features in architecture. Koolhaas Floriac House incorporates partitions that fold down and disappear into the floor for example [Rem Koolhas, Floriac House, Bordeaux, France, 1995]. Going one step up in scale, the re-use of modules is another possibility and has a long history in architectural design. Archigram's archetypal plug-in city is the pre-cursor of many of the schemes that can be placed in this space. Kurukawa's Nakagin Capsule Tower is a constructed example, in which standardized cubicle units are fixed to a central tower containing services and circulation [Kisho Kurukawa, Nakagin Capsule Tower, Tokyo, Japan, 1972]. At least in principle they are designed to be removed and re-located. Projects by Wes Jones, especially the project Pro/Con then appear to include the various uses of components and modules in the same scheme [Wes Jones, Pro/Con, Los Angeles, USA, 2004].

Spatial features

Spatial features can be transformed, ranging from location, topology, and orientation, to form, the link between inside and out and internal partitioning. The location of buildings can change during the occupation life-cycle. One particularly interesting example is Böhtlingk's Markies, an extendable camper trailer that is able to fold out its sides to create a larger enclosure [Eduard Böhtlingk, Markies, the Netherlands, 1985-95]. Actual buildings that draw on such principles are more transportable rather than mobile necessarily and frequently combine the re-configurability of different units to establish different architectural topologies. Lot-ek's Mobile Dwelling Units are based on standard shipping containers and designed to follow people to wherever they live [Lot-ek, MDU (Mobile Dwelling Unit, Transportable, 2002]. Even when the site location of a building remains fixed, some radical changes can be achieved through changing the orientation of parts of an adaptive building. Sturm and Wartzech explore the impact on the relationship to the building's relationship to its environment [Sturm und Wartzech, Kubus, Dipperz, Germany, 1996]. And beyond rotation, there are also a number of design projects that play with adapting the form of buildings. Changeable roof covers are probably the most common type of building in this category. There are various sports stadia the roofs of which can be opened and closed, depending on the weather conditions. Studio Gang O'Donnell's Theatre takes a similar strategy to a cultural performance space, allowing directors to open the roof, reflecting what is currently being played [Studio Gang O'Donnell, Bengt Sjostrom Starlight Theater, Rockford Illinois, 2003]. May be a slightly less common way to adapt forms are buildings that adapt in size, but relatively recently there have been a number of projects that are based on what might be called 'drawer' designs, allowing inhabitants to pull out parts of the building to adapt the interior space. One interesting example in this context is Seifert & Stöckmann's Living Room project that incorporated an extendable room cantilevered over an external void when drawn out [Seifert & Stöckmann, Living Room, Gelnhausen, Germany, 2005]. Taking the adaptation of form to its extreme, are those examples that change the actual shape of buildings in a more fluid and less prescribed fashion. Hyperbody's Muscle Re-configured highlight interesting possibilities combining fabric architecture and flexible hydraulics [Hyperbody, Muscle Re-configured, Delft, The Netherlands, 2004]. Buildings can also be designed to be adaptive in their spatial topology. This concerns designs where the relationship between individual architectural units (modules or rooms) is not fixed during the occupancy of a building. This can be achieved through physical re-configurations. Price's seminal Generator Project provides some of the key inspiration in this area [Cedric Price, Generator Project, Project, 1978]. Achieving the above is technically very challenging, certainly when exterior surfaces are involved. However, there have been a number of interesting projects that focussed on physically adaptive topologies in the interior space. Shigeru Ban's Naked House plays with this idea by enclosing a number of rooms on wheel bases in the larger open-plan volume of a residential propterty. Only service areas are fixed, while living quarter can be re-arranged at will for different purposes [Shigeru Ban, The Naked House, Hadano, Japan, 1997]. There are also efforts to increase topological flexibility through communication technologies. Such hybrid spatial topologies consist of multiple physical spaces, typically remote to each other that are linked through audio and video. These technological links, especially when persistent link other locations as if they were close by and part of the same architectural configuration. Some times this is direct and predominantly designed for domestic environments as in the ComHome project [Stefan

Junestrand, ComHome proejct, KTH, Stockholm, Sweden, 1999]. Other projects have explored the use of a mediating 3D virtual space for an inhabitant driven hybrid spatial topology in a work setting such as the Mixed Reality Architecture prototype [Holger Schnädelbach, Mixed Reality Architecture, Multiple Sites, UK, 2003-2010]. A very prominent adaptive feature in building architecture is configuration of the inside/outside link. All occupied buildings have doors and windows but there are some projects that highlight particularly interesting possibilities in this area. Early modernist seemed to have a particularly strong interest in this form of adaptation. Gaudi's Casa Batla includes an ornamental exterior window panel that can be retracted up into the ceiling to create a balcony [Gaudi, Casa Batlo, Barcelona, Spain, 1904-106]. A similar strategy was followed by van der Rohe in his Tugendhat House that included a glass partition that slide into the floor to open the building up to outside [Mies van der Rohe, Tugendhat House, 1929-30, Brno, Czech Republic]. On a larger scale, and using an entirely different and more ambitious engineering solution, Hoberman's Arch project translates this idea to stage design, connecting back to the principle of stage curtains [Chuck Hoberman, Hoberman Arch, Salt Lake City, USA, 2002].

Technical Systems

The final element of adaptation concerns technical systems. In Adaptive Architecture, they are those systems, consisting of sensors, systems (software) and actuators, which actually produce adaptations when they are not entirely based on human intervention. Technical systems are at once elements of adaptation (they are being adapted) and a method of adaptation. Technical systems will be discussed in detail in the Method section.

Method

On a practical level, how is adaptation done in Adaptive Architecture? This section discusses the following categories: human intervention, sensor based, systems and processing and finally actuation.

Human Intervention

Conscious and intentional adaptations require a person to deliberately trigger an adaptation in a building, i.e. through human intervention. This can be direct and inhabitants will be able to move, rotate and re-position architectural elements that are designed for this purpose. Sometimes this is simply through manual adaptations as for example in Steven Holl's Fukuoka Housing project, where inhabitants are able to re-orient partitions to their requirement [Steven Holl, Fukuoka Housing, Fukuoka, Japan, 1991]. This same strategy is the basis for work in hybrid spatial topologies, creating architectural spaces that are linked through audio-visual connections. The previously introduced Mixed Reality Architecture allows its inhabitants full manual control over its hybrid spatial topology to support their current needs [Schnädelbach, Mixed Reality Architecture, Multiple Sites, 2003-2010]. There are also examples where this intentional control is mediated through technology and one of the earliest examples of remote control operation in a building context is Van der Leeuw House that allowed a glass partition be moved in this way [Jan Brinkman and Cornelis van der Vlugt, Van der Leeuw House, Rotterdam, 1928-29]. Finally, there is also indirect control, but fully intentionally activated through technical systems. For example, this typically occurs when an inhabitant sets a specific temperature for the interior of their building via a HVAC system.

Sensor Based (technical data source)

Sensors find widespread application in Adaptive Architecture and provide the data that automatic adaptations are based upon. These can detect data such as inhabitant activities, environmental information and information about objects, previously introduced in 'Reaction to what? - Logical sources driving adaptation'. This section discusses in more detail with what technical methods this can actually be achieved; how this is technically done.

There is a multitude of sensors that can provide personal data in a building context and this has been steadily growing over the last few decades. There are a number of different types of personal data that can be made relevant in a building context. Only relatively recently physiological data, such as heart rate or skin conductance, has become practical to record and make available within Adaptive Architecture. Schnädelbach's ExoBuilding prototype, a piece of Adaptive Architecture that breathes with its inhabitants and sonifies their heart beat explores the design space when such data and the building fabric are linked [Holger Schnädelbach, ExoBuilding, University of Nottingham, UK, 2009]. Sensors embedded into buildings can detect the location of its inhabitants to varying degrees of accuracy. These can involve an infrastructure where sensors are worn by participants that are then detected by receivers placed in the building infrastructure, as for example in the Active Badges set of technologies [Roy Want, Active Badges, Olivetti, Cambridge, UK, 1992]. Detecting the location of inhabitants can also rely on sensors embedded into the building fabric, for example those that detect the motion of inhabitants similar to an intruder alarm. Mozer's Adaptive house experimented with such sensors to explore building infrastructures that 'programme themselves' rather than having to rely on manual configuration [Michael Mozer, The Adaptive House, Boulder, Colorado USA, 1997]. Sensors can be used to identify individuals and a number of technologies are available, such as smart cards for example. Sobeks R128 House provides an interesting example in this space with its voice operated entrance door, opening only when one of a number of pre-recorded voice samples is recognised [Werner Sobek, R128 House, Stuttgart, Germany, 1999-2000]. Finally, the activities of people (e.g watching TV, preparing food) might be detected as a driver for adaptations and it is also possible to combine the above data streams to learn about group behaviours over time. As previously highlighted, sensors can also detect environmental conditions inside and outside of a particular Adaptive Building. There are sensors for wind speed, temperature, light levels, air pressure, air quality and noise levels among others. Returning to the previously mentioned research Eco House, many projects in sustainable architecture will combine a number of those sensors [Derek Trowell Architects, The BASF House, 2008, University of Nottingham, UK]. The final sensor category is concerned with detecting objects. In supply management, RFID tags are regularly embedded into product packaging and in the construction industry also into building components and elements. Bar codes are ubiquitous in retail. Both can help identify the route of a product and estimate its arrival time on site for example. The resulting information about an object's identity and location and possible information that can be drawn from analysing the relationships between multiple objects can then be made available for building adaptation, as already highlighted in 'In reaction to'. Another interesting category of object sensors is concerned with the object's condition. Sensors in this category currently allow the deviation from pre-specified parameters, for example to detect whether a product has been kept cool during transit.

Systems and processing

Data from sensors in isolation is rarely very powerful. It is the combination of multiple data streams that allows more complex analysis and reasoning. Frequently, a piece of middleware software is responsible for reading data, both directly triggered by human intervention and caused by sensor output, processing that data and then pass it on to the relevant actuators (see for actuation in the following section). Such software reads in data from sensors and needs to have ways to deal with erroneous data and erroneous interpretations of data. Frequently such software provides some data visualisation to allow people to be more aware of the underlying data flow. This then gives rise to providing the appropriate level of control to inhabitants to adjust their building system accordingly. Both research labs and commercial organisations have developed software that fulfils this role. Greenhalgh's Equator Component Toolkit developed at Nottingham [Chris Greenhalgh, ECT, Nottingham, UK, 2005] and Bernardet's IQR [Bernardet, IQR, Barcelona, Spain, 2002] were developed for very different purposes but show clear overlaps in the way that data connections are structured and exposed to the developers. Very much related to these, Processing is a very popular set of tools for prototyping interactive and adaptive demonstrators, even though it lacks the ease of use of visual programming [Ben Fry & Casey Reas, Processing programming environment, MIT, Cambridge Massacusetts, 2005]. In the construction industry, the area of building management systems covers that ground. A building management system will draw on sensor data, configurations and data learnt over time to adapt buildings to the current circumstances. Frequently, more complex buildings will draw on more than one building management system. The University of Nottingham Jubilee Campus is a good example, where there different systems for environmental controls, lighting and access [Michael Hopkins, Jubilee Campus, Nottingham, UK, 1999]. The above middleware platforms tend to run on centralised standard computers. More recently, there has been a push to distribute the processing of data out and the emergence of sensor networks is a direct result from this. Instead of being controlled and powered centrally, sensors and actuators become embedded with some processing and communication capabilities that allow for more rapid adaptations to changing stimuli.

Actuation (technical data sync)

Non-manual adaptations in buildings depend on a variety of actuators to execute the intended effects. These range from lighting, vents, climate control, motors, hydraulics and pneumatics, phase change materials, communication links, to media displays of varying types. Actuators are driven by systems and processing technologies (described above) and are principally responsible for creating the desired effects in Adaptive Architecture (discussed below).

In adaptive buildings, lighting can frequently be influenced to create certain effects. Whether it is to create a certain ambiance or to save energy, lights can be switched, dimmed and the colour spectrum changed. Toyo Ito's Tower of Winds is an early example of a media façade that plays with lighting to represent local information [Toyo Ito, Tower of Winds, Yokohama, Japan, 1986]. There is then a whole series of technologies that are implemented to move architectural components or elements. Motors are employed to move parts of architectural structures into different positions. In certain circumstances, this strategy can totally transform building as is the case DRMM's Sliding house that incorporates a moveable structure that can slide over the main residence to variably enclose spaces and open up the surrounding landscape to differing views [DRMM, Sliding House, Suffolk, UK, 2009]. Hyraulics are another technology very frequently employed, particularly for adapting spatial features in adaptive buildings. Koolhaas' Floriac House includes a central room or platform that can be raised to allow the wheel-chair bound owner full access to all levels [Koolhaas, Floriac House, Bordeaux, France, 1995]. Very much related to this, pneumatic technology is based on the same principle, but achieves the effect with air pressure. Osterhuis' Adaptive Façade project envisaged using pneumatic actuators to create variable openings in a dynamic building façade [Kas Osterhuis, Adaptive Façade, un-realised project, 2003]. Still concerned with movement, another technology to mention is that of phase change materials. These are based on the principle that material expands with increases in temperature and the engineered pistons are already frequently used in green houses. The same technology has recently been applied to a building prototype exploring deployable external insulation, façade insulation that gets moved in placed when required by external conditions [Deployable.Org, D.E.I. Pavilion, London, UK, 2008]. Technologies to trigger movement are then used for more mundane things, like the automatic opening of vents, smoke outlets in fire safety and in running ventilation systems. Another interesting area of actuation is data flow and communication. It is conceivable that Adaptive Architecture might take control of digital communication and the networking infrastructure. The ongoing Homework research project is already looking at the technical and interactional challenges of making those networking decisions better readable by inhabitants [Tom Rodden, Homework Research project, Nottingham, UK, 2009-2012]. It is clerly conceivable how this could be extended to actuating resource supply of water and electricity, especially in the light of micro-generation projects and their relationship to the relevant national grid.

Finally, media displays in various forms can be seen as specific forms of actuation. A number of smart home projects have been playing with adapting music and other media to different contextual circumstances. Spubroek NOX' Son-O-House creates an interactive sound architecture that uses data from sensors to generate a live soundscape which depends on the presence and behaviour of inhabitants [van der Heide, Spubroek (NOX), Son-O-House, Eindhoven, The Netherlands, 2004]. Videos can be displayed on many media façade projects that have been developed. Beyond those there might also be real potential in technologies to generate smells [Strong & Gaver, Feather, Scent and Shaker: Supporting Simple Intimacy (Research project and demonstrator), 1996].

Effect

Effect can be described as the category that are work in all other categories is aimed at. It is the effect of adaptations described here that creators ultimately aim for. The following presents effects on the environment enclosed by Architecture, the permeability of configuraitons and the resulting effect on inhabitants.

Environment enclosed by Architecture

Adaptations have impact on the environment that the architecture encloses. Light levels inside a building are affected by artificial lighting, blinds, shutters and reflectors in the building concerned but also in buildings nearby. Returning to InQbate, introduced earlier, this learning and teaching environment includes 3000 controllable LED lights embedded into the ceiling that allow for complete changes to the colour temperature of the overall space and/or regions of the space [Sussex University, InQbate, Sussex University, UK, 2007]. The air quality can be affected by through changes in airflow that might be in turn a reaction to the detection of certain environmental parameters such as raised C02 levels. The temperature in buildings is adapted whether that might be through natural cooling, assisted natural ventilation or indeed full climate control. There are projects that specifically target a specific sound landscape, sound volume and composition. Some times sound processing is used to simulate the effects of another physical environment as is evident in FTL's Music Pavillion, attempting to replicate concert-hall quality sound outdoors [FTL Design Engineering Studio, Carlos Moseley Music Pavillion, 1991, USA]. Another way of having impact on the environment enclosed by architecture is through adaptations of density of information that is presented. In this context, surfaces might rapidly change from being background and ambient to full information displays, for example displaying text instead of ornamental patterns.

Permeability

There is also the related environmental effect of permeability of architectural configuration. Permeability can be increased through the opening of doors and gateways, making particular routes available to inhabitants for particular circumstances. The inverse is achieved through closing links and/or through selected permeability where only certain parts of a given population might traverse through certain parts of the space. In addition, the permeability of architectural configurations can be manipulated on a physical as well as on a virtual level and this aspect has already been discussed in 'Spatial Features' in 'Elements of Adaptation'.

Effect on inhabitants

In most cases, it is the effect on inhabitants that designers of Adaptive Architecture work towards. The most fundamental concern is centred on how it impacts inhabitants, where inhabitants are individuals, groups of individuals and organisations. This can be concerned with inhabitant levels of comfort, for example via regulating the indoor climate and levels of convenience, through taking away repetitive chores in automation. Inhabitant safety and security is a key concern and results in places being locked down automatically to stop intruders and opened up automatically to avoid harm, for example in a fire. Certainly in the context of this framework, if not in the entire field of Adaptive Architecture, the effects on inhabitants feel currently underexplored and this is an area that would warrant some further investigation.

Design strategies in Adaptive Architecture

To take the discussion away from the perspective of the very detailed and more fine-grained categories introduced above, it is now worth highlighting a number of overall strategies that are employed in the design for adaptiveness to conclude the presentation of the framework. Strategies draw on the previously introduced categories but are abstracted from them. They are designed to describe important aspects of the design palette that creators have access to. The following strategies will be discussed: mobility, levels of prescription, reusability and standardisation, automation and design for human intervention and building independence.

Mobility

Architects have frequently explored mobility as a design strategy to allow buildings to better respond to changes around them. Most architecture is fixed to one location. In adaptive Architecture, inspiration is frequently taken from related mobile infrastructure such as caravans, trailers, boats and even space ship design to develop building the respond to inhabitants' needs. This results in transportable and then also truly mobile architecture. Relevant example have mostly been covered in 'Spatial features' and 'Elements and Modules' subsections of 'Elements of Adaptation.

Levels of prescription

One might also distinguish two overall strategies when it comes to the levels of prescription of the potential adaptations in a building. One end of the spectrum, things are left open, the building framework being designed to cope with the largest amount of conceivable interior adaptations which has been proposed by Habraken as a formal design philosophy (Habraken, 1972). At the other end of the spectrum sits a strategy to heavily prescribe all possible adaptations, in an attempt to anticipate what occupants of such a building might require over the life-time of the building. Examples for both ends of this design principle spectrum are to be found across the entire framework.

Re-use

The third strategy identified here revolves around re-useability and standardisation. Building can be designed in a bespoke way, where each and every component is made to fit that particular building project. In most buildings some form of standardisation is present, all the way to pre-fabricated buildings where nearly all components are standardised. In this case, components should be interchangeable which should lead to a more adaptive design.

Automation - Human intervention

The chosen level of automation is another critical strategy in this context. Adaptive buildings can be designed specifically for inhabitant intervention. In those cases, inhabitants will be able to move, rotate and re-position architectural elements that are designed for this purpose, whether this is manually or through assisted power systems. Frequently adaptive architecture relies on some level of automation. Sometimes this automation is based on non-reactive scripting, i.e. making things adapt according to a pre-configured time frame and programme. Automation is then introduced so that a building becomes responsive to a number of various stimuli. The discussion of the detailed aspects on automation can be found in the method section with a number of relevant examples. The tension between manual and automatic adaptations is a central concern in the design for adaptiveness, frequently manual and automatic adaptations are combined and the choice is fundamentally tied to the original motivations of the creator.

Time Scales

Design for adaptiveness must consider the time scale in which adaptations can reasonably be expected. There are very short time scales to be designed for in Adaptive Architecture, where responses to stimuli are rapidly reflected through adaptations, very similar to the interaction with a computer interface. There slower time scales to consider that are may be relevant during the course of a particular day, where inhabitants and their usage patterns drive building adaptations. There are then also much longer timescales. Over decades or even centuries, designing for Adaptiveness is probably much more concerned with leaving room for adaptations and for the un-anticipated. Interestingly, it is the technology systems that allow for rapid adaptations or immediate interactions with a building that are the most difficult to adapt over the longer term.

Inhabitant focussed - Independence

Finally, the design space also incorporates a dimension or strategy that addresses the level of independence of a building from its inhabitants. Adaptations in most Adaptive Architecture are in some way related to inhabitants, adapting to their requirements, even if this is indirectly by for example adapting to the environment or objects. It is also clearly conceivable for building to adapt with their own purpose, i.e. not reactive architecture. Here building might 'listen' in to their own emerging data stream and pattern and evolve adaptive behaviours over time without recourse to external stimuli or any reference to what types of conditions are created.

Conclusion

This paper has presented a conceptual framework of Adaptive Architecture, with the aim to give readers a broad overview of motivations and drivers before introducing the key components of adaptive architecture as logical data source, elements of adaptation, methods and effects. This was concluded with a discussion of the various strategies that architects have at their disposal. Categorisations like the one proposed in this paper always have similar issues. They suggest that the categorisation is itself clear-cut, while in many cases there are potential overlaps and examples easily fit into multiple categories. There is also a danger that differences are emphasised over connections, especially when a framework like this is presented in a sequential order as expected in academic writing. However, this framework is work in progress and does benefit from a more interactive digital presentation in which it was developed and is currently being refined in.

This lets readers explore the relationships between categories in a more dynamic way. Both in its paper form and in its more interactive form, it arguably presents a useful resource for new and emerging projects to be related to historical and existing work, with a view to provide an integrated overview of the field of Adaptive Architecture.

In future work, it is the area of 'effects on inhabitants' that is now of most interest to us in terms of further research, as this seems currently underexplored. In our lab we have recently started to focus on the effects on inhabitants of buildings that are driven by physiological data (Schnädelbach et al., 2010). A currently being analysed controlled study of our prototype points to the possibility that such environments have a measurable effect on the physiology of inhabitants and we are aiming to explore this further in detail.

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References

BRAND, S. (1994) How buildings learn : what happens after they're built, London, UK; New York, USA, Viking.

BULLIVANT, L. (Ed.) (2005) 4dspace: Interactive Architecture, Wiley-Academy.

ENG, K., BAEBLER, A., BERNARDET, U., BLANCHARD, M., COSTA, M., DELBRÜCK, T., DOUGLAS, R., HEPP, K., KLEIN, D., MANZOLLI, J., MINTZ, M., ROTH, F., RUTISHAUSER, U., WASSERMANN, K., WHATLEY, A. M., WITTMANN, A., WYSS, R. & VERSCHURE, P. F. M. J. (2003) Ada - Intelligent Space: An artificial creature for the Swiss Expo.02. IEEE International Conference on Robotics and Automation ICRA 2003. Taipei, Taiwan.

HABRAKEN, N. J. (1972) Supports: An Alternative To Mass Housing, London, Architectural Press.

HARPER, R. (2003) Inside the smart home, London ; New York, Springer.

KRONENBURG, R. (2007) Flexible : architecture that responds to change, London, Laurence King.

PRICE, C. (2003) The Square Book, Chichester, UK, Wiley&Sons.

ROAF, S., FUENTES, M. & THOMAS, S. (2007) EcoHouse: A Design Guide, Oxford, Architectural Press.

ROGERS, Y. (2006) Moving on from Weiser's Vision of Calm Computing: Engaging UbiComp Experiences. IN DOURISH, P. & FRIDAY, A. (Eds.) UbiComp. Orange County, USA, Springer.

SCHNÄDELBACH, H., GLOVER, K. & IRUNE, A. (2010) ExoBuilding - Breathing Life into Architecture. NordiCHI. Reykjavik, ACM Press.

SCHNÄDELBACH, H., PENN, A. & STEADMAN, P. (2007) Mixed Reality Architecture: A Dynamic Architectural Topology. Space Syntax Symposium. Istanbul, Turkey, Technical University Istanbul.

STREITZ, N. A., SIEGEL, J., HARTKOPF, V. & KONOMI, S. I. (Eds.) (1999) Cooperative Buildings, Berlin, Germany, Springer.

TSCHERTEU, G. (2009) Mediaarchitecture. Vienna, Austria, Media Architecture Group.

WILLMERT, T. (2001) The Return of Natural Ventilation. Architectural Record, 189, 137.

ZELLNER, P. (1999) Hybrid space : new forms in digital architecture, London, Thames & Hudson.