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A REVIEW OF CLIMATE CHANGE ADAPTIVE MEASURES IN ARCHITECTURE WITHIN TEMPERATE CLIMATE ZONES

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ABSTRACT

Since a large portion of greenhouse gases are emitted by the building sector, there has been a push towards sustainable low energy architecture, which could help mitigate the effects of climate change. Although climate change is considered inevitable, adaptive measures must be taken in the field of architecture to alleviate its impact. Creating an overview of the state of the art in the field of architecture as it adapts to climate change will help identify the problems and possibilities of architectural adaptation.

The aim must be to create buildings that are as suitable to the current climate as they are to the climate of the future and maintain an ability to resist the impacts of climate change; this ability to resist potential change is defined as adaptive capacity. It is challenging to reconcile the energy requirements for contemporary buildings with rising temperatures and extreme weather in temperate climate zones. The literature on the subject is explored through iterative searches in scientific databases.

In discussions about the possible adaptations to climate change, there needs to be a focus on human adaptation facilitated by architecture and the built environment's utilization and support of ecosystem services in adaptation strategies, since the scope of climate change reaches beyond the singular building. There are plenty of strategies and technologies from which to draw but little focus on how these should support the design of a building and its inhabitants. In the future it will be necessary to look at the adaptive capacity of a building itself and how the building can benefit its surroundings.

KEYWORDS

architecture, adaptation, climate change, built environment, user involvement, temperate climate

1. INTRODUCTION

Climate change is one of largest challenges facing society. The consequences permeate through all levels of society, and an imminent response is needed to handle them. The changes can range from moderate changes in local weather patterns to increasingly extreme events. The specific consequences of climate change are uncertain and depend largely on global attempts to lower

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the emissions of greenhouse gasses. Therefore, adaptations must be made on the background of the emission scenarios presented by the IPCC (2014).

This article focuses on the issues facing architecture as it adapts to the threats of climate change. There have been significant efforts made to mitigate the impacts of climate change through energy reductions in the building sector, but with less focus on buildings adapting to the seemingly inevitable changes in the climate. Therefore, an overview of climate change adaptations in architecture is necessary. Although climate change imposes different challenges based on the zones affected, this paper will primarily focus on the challenges facing architecture in temperate climate zones.

Many cities, municipalities and countries already have plans for adaptation in place (City of Copenhagen, 2015; Sovacool, D'Agostino, Rawlani, & Meenawat, 2012), though most of these focus on the challenges of handling the changes in the urban spaces. Urban design has been focusing on mitigating flood risks and urban heat island effects in many design and research projects. The potential for adaptation to climate change in building architecture is less prominent. This is slightly paradoxical, considering that most of a city's runoff water originates from its buildings (Kaźmierczak & Cavan, 2011; Sjöman & Gill, 2014). Buildings, if not properly adapted, can be major contributors to urban heat island effects and greenhouse gas emissions from increasing cooling demands and use of electric cooling systems (Buchin, Hoelscher, Meier, Nehls, & Ziegler, 2016). Should the increased cooling demands not be met, health hazards related to overheating could become rampant as temperatures rise. Since we spend around 90% of our time indoors, the issues caused by climate change must be addressed in the interior of buildings as well as the exterior. It is essential that the inhabitants are addressed in the adaptations (Altomonte, Rutherford, & Wilson, 2015; Brunsgaard, Knudstrup, & Heiselberg, 2012; Hansen, Olesen, & Mullins, 2013).

Buildings standing today are designed and optimized for climates of the past. New buildings will likely face changing climates through their lifetimes, giving rise to issues with regard to energy frame, indoor climate and exposure to extreme events that were not a concern at the time of construction. Architects and engineers will have to consider a less stable climate and design buildings to last their lifetimes. This is a major departure from how participants in the building sector currently act, where designs that stretch beyond the near future of delivery is rare. The increasing requirements and regulations for energy use in the building stock could make new buildings more vulnerable to the effects of rising average temperatures, due to scope and focusing largely on heating in legal requirements within temperate countries (Pathan, Mavrogianni, Summerfield, Oreszczyn, & Davies, 2016).

The definition of adaptation utilized in this article is adaptations to the consequences of climate change. The aim of the review is to provide an overview for building design and architecture professionals that adapt buildings to future changes in the climate, not small or cyclical changes that happens to architecture in normal use. Adaptations of buildings to changing functions and users are not considered, unless they provide a link to user interaction as an adaptive measure to climate change. Nor are adaptations to microclimatic and seasonal changes discussed in detail, unless they are part of a holistic adaptive strategy to mitigate the effects of climate change. While these topics are relevant from the perspective of sustainability, they need to be connected directly to the long-term adaptability of buildings to the effects of climate change to add value to this review.

Within the field of adaptation to climate change, there are predispositions toward choosing certain solutions. In several instances, the literature might be conflicted or may contradict practice (Gul & Menzies, 2012; Marsh, 2017; Roders & Straub, 2015). The major part of this conflict is between climate change adaptation and climate change mitigation, even though the two approaches are supposed to support one another. The singular focus on climate change mitigation in sustainable architecture and building codes (especially in Northern Europe) have created buildings that on paper are energy efficient but suffer from poor indoor climate and especially problems with overheating. In the worst cases the buildings consume more energy compared to buildings of lower energy certifications (Brunsgaard et al., 2012; Marsh, 2017). This problem will only grow if the climate shifts toward warmer averages.

Following the building regulations' preference to mitigation compared to adaptation, there are generally few concrete requirements for the adaptive measures of buildings. Therefore, economic incentives become primary; most adaptation strategies are deemed as expensive and uncertain by both builders and users (Gul & Menzies, 2012; Roders & Straub, 2015).

Experimental studies might also contradict simulation studies and therefore change the perception of the solution. This happens because the green elements in building design (Buchin et al. 2016) can be based on assumptions in the simulation models that do not always scale with reality. For example, the assumed efficiency of a building's cooling capacity through evapotranspiration might be overstated and its water retention capacity could be at the cost of high maintenance or large frontloaded investments.

This article will delve into these conflicts and give an overview of the state of the art within the field. The review will focus solely on architecture, which incorporates building elements, details, and singular technological solutions. The article addresses the whole building and all elements affecting itself and its inhabitants. Each category is considered individually before a discussion that investigates the field as a whole and considers all knowledge collected and analysed in the review.

1.2 Definitions

This section will seek to define certain terms and concepts used throughout the paper.

- **Sustainability:** This paper focuses primarily on environmental sustainability as opposed to social or economic sustainability. As such, this mainly relates to the mitigation of climate change through lower emissions of CO_2 in buildings or through the building process. The source of the lowered greenhouse gas emissions could be lowered heating or electricity demand, or embedded energy in materials, etc. (Bejder, Knudstrup, Jensen, & Katic, 2014; Knudstrup, Hansen, & Brunsgaard, 2009). In this context sustainability is somewhat interchangeable with climate change mitigation.
- **Adaptation:** Adaptation is defined as the ability of a system to adjust to a new baseline. The range of possible adaptation is defined as the adaptive capacity as per Smit (2006) and by the IPCC (2014).
- **Resilience:** Resilience is separated from both sustainability and adaptation as a description of the ability of a system, in this case building design, to recover from a disturbance of the baseline, similar to the description in Lomas & Ji (2009).

2. METHODOLOGY

The following review will systematically explore the current state of the art within architectural adaptation to climate change through iterative block searches. The iterative process allows the searches to change at each step to ensure thorough coverage of the field.

The searches were made in Scopus, since experience has shown it to be the most comprehensive search engine for architectural literature. The searches were supported by the literature, which added contextual knowledge outside the systematic search but was not included in the review. This was a determining factor in shaping the iterative search.

To guide the search a group of questions was defined. These questions were designed to narrow the path of the search and identify unexplored avenues of research. To ensure that the literature was up to date, only literature from the last ten years was included within the search. While arguments can be made for going further back in time, literature on adaptations to climate change did not start to proliferate until recently. Moreover, the awareness of the vulnerabilities in the building sector exposed by climate change have only become apparent since dissemination in mainstream consciousness during the last decade.

After conducting the searches, the author performed a manual sorting based on inclusion and exclusion criteria, removing unrelated literature and focusing on the objectives of this article. Manual sorting was done at two stages: first, the articles were sorted based on their title and abstract, which left around 25% of the literature. A second sorting based on the full article revealed articles that did not adhere to search criteria or had a different focus than the title and abstract indicated. The remaining articles are reviewed in the results section.

The core search terms were keywords relating to *architecture* or *building* and *design*. This targeted the search sufficiently at architecture-oriented results without being too narrow. The first search relied on the indexed term "architectural design," which proved to be too exclusionary for the field of research.

This exposed a larger problem with doing a systematic review within the area of adaptive architecture, since a great deal of the professional vocabulary is used interchangeably. Adaptations can interchange with resilient measures, although both are distinct within risk management and climate science.

2.1 Questions

The search questions were defined to narrow the field of study. The review has a Western bent for two reasons: 1) differences between climate zones are vast, so to keep the focus of this article manageable only one climate zone was chosen and 2) current temperate climate zones face difficulties by moving from dominating heating demand to cooling demand while maintaining high energy standards.

2.1.1 Questions:

What measures of adaptation to the effects of climate change are used in buildings and how are they integrated in the architecture?

How is the inherent uncertainty in the development of the climate changes considered in these adaptations?

Can these technologies feasibly be implemented in housing in a temperate lowland climate?

2.1.2 Inclusion criteria:

Architecture on the building scale.

Technologies should be discussed in relation to the architecture.

Temperate climate.

Impacts in coastal areas.

Adaptation in relation to climate change.

2.1.3 Exclusion criteria:

Tropical or arctic climates if the material is on indoor climates and energy frame.

Urban, mobilities or design/detail-element scale.

3. RESULTS

The iterative search resulted in four distinct combinations that feasibly could contain a major portion of the state of the art. The author recognizes that the review was limited to literary sources lacking first-hand practical knowledge, interviews and case studies and therefore did not cover every aspect of the field. As a major part of this field is still speculative, a literary review is deemed relevant for the state of the art.

3.1 Search iterations

3.11 Search 1: Introductory

The first search, which focused on the keyword *architectural design*, was relatively wide. Because most substantial additions to the literature are found in journal papers, conference papers were not included in this search. Further searches did not have this restriction. The inclusive keyword “architectural design” (in quotations) was used to eliminate papers outside the scope of architecture and therefore irrelevant to this review.

TABLE 1. Search Combination 1.

Search Combination 1					
Search Terms				**Results**	**Reduction**
TITLE-ABS-KEY (climat* AND adapt* AND architect* AND building*)				533	
Inclusion Criteria		*Exclusion Criteria*			
Language:	English	Language:	—	523	–10
Keyword:	Architectural design	Keyword:	Tropics	156	–367
Source:	Journal Paper	Source:	—	89	–67
Subject	—	Subject	—	—	—
Publication Year:	2017–2007	Publication Year:	—	82	–7
1st manual sorting based on title and abstract compared to overarching criteria and questions				31	–51
2nd manual Sorting based on further reading				18	–13

3.1.2 Search 2: Resilience

Resilience is a term linked to adaptation. While the terms are not interchangeable, they have a similar focus. Resilience is a vague term with several definitions (Zhao, McCoy et al. 2015), but the overall focus of the concept is on a system's ability to return to a stable baseline after the impact of an event. Regenerative design is the active improvement from the baseline by the building design through the active regeneration of a natural system, or their functions, that exist on and around the building site (Du Plessis, 2012; Pedersen Zari, 2015). Essentially, regenerative design goes beyond sustainability, which sustains the status quo, and regenerates the damage human influence have wrought. Regenerative architecture would thus create a larger positive influence on the building site and its surroundings than the negative impact that creating a building on the given site would have.

The second search attempted to uncover resilient buildings in the context of building design and architecture. The search terms were ordered into a base used in consecutive searches. The base was (architect* or (building and design)) in the keywords. To focus on building resilience in the context of adaptations to climate change (resil* and adapt*) were the search variables.

3.1.3 Search 3: Biomimicry and Bioclimatism

As the natural world has evolved and adapted over 4.28 billion years (Dodd et al., 2017), it is natural to look at the adaptive capabilities of natural systems. Applying these processes to design is defined as biomimicry. Biomimicry refers to the reinterpretation of natural functions and processes, often as abstraction. Adaptation to climate change in architecture can benefit from biomimicry, since it changes the understanding of buildings as immutable objects to buildings as changing systems that can evolve and adapt as their natural counterparts do.

TABLE 2. Search Combination 2.

Search Combination 2					
Search Terms				Results	Reduction
Base:					
KEY (architect* OR (design* AND building*))				*408226*	
Variables:					
TITLE-ABS-KEY (resili* AND adapt*)				392	–407834
Inclusion Criteria		*Exclusion Criteria*			
Language:	English	Language:	—	388	–4
Keyword:	—	Keyword:	Network Architecture	310	–78
Source:	—	Source:	—	—	—
Subject:	—	Subject	Major irrelevant subjects	140	–170
Publication Year:	2017–2007	Publication Year:	—	122	–18

Architecture that borrows its aesthetics from nature is defined as biomorphism by Pawlyn (Pawlyn, 2011), which is of little interest to the review.

To widen the search bioclimatism is also interesting, to some degree, in architectural adaptations, e.g., studies on the adaptive capabilities of vernacular architecture. Care must be taken when incorporating articles on bioclimatism because bioclimatic and vernacular architecture is about the design of the existing climatic conditions and not what *will become*. However, articles discussing the resiliency of bioclimatism are useful to this review. A large number of the articles concerning bioclimatism and vernacular architecture were discarded since they described relatively small climatic niches outside the temperate zones and did not take into consideration potential changes.

3.1.4 Search 4: Extreme Weather

Extreme weather resulting from climate change will likely manifest as flooding, storms, or heatwaves. Therefore, the literature on these subjects in relation to the built environment is essential.

The search included attempts to locate articles on the subject of architectural adaptations to extreme weather. There are many responses to the extreme consequences of climate change, but few are adaptive and most tend towards entrenchments that just shift problems elsewhere.

TABLE 3. Search Combination 3.

Search Combination 3					
Search Terms				**Results**	**Reduction**
Base:					
KEY (architect* OR (design* AND building*))				*408226*	
Variant:					
TITLE-ABS-KEY (climat* AND adapt* AND (bio*))				188	–408038
Inclusion Criteria		*Exclusion Criteria*			
Language:	English	Language:	—	184	–4
Keyword:	—	Keyword:	—	—	—
Source:	—	Source:	—	—	—
Subject:	—	Subject	Major irrelevant subjects	161	–23
Publication Year:	2017–2007	Publication Year:	—	143	–18
1st manual sorting based on title and abstract compared to overarching criteria and questions				28	–115
2nd manual Sorting based on further reading				14	–14
Removing duplicates from previous searches				9	–5

TABLE 4. Search Combination 4.

Search Combination 4					
Search Terms				**Results**	**Reduction**
Base:					
KEY (architect* OR (design* AND building*))				*408226*	
Variant:					
TITLE-ABS-KEY (adapt* AND ((heat AND wave) OR flood*))				142	–408084
Inclusion Criteria		*Exclusion Criteria*			
Language:	English	Language:	—	137	–5
Keyword:	—	Keyword:	—	—	—
Source:	—	Source:	—	—	—
Subject:	—	Subject	Major irrelevant subjects	65	–72
Publication Year:	2017–2007	Publication Year:	—	57	–8
1st manual sorting based on title and abstract compared to overarching criteria and questions				18	–39
2nd manual Sorting based on further reading				13	–5
Removing duplicates from previous searches				6	–7

For instance, building dykes to handle flooding from sea rise and storms only shifts the problem to the unprotected edge of the dykes (Watson & Adams, 2011).

3.2 Review of results

The overall picture of the results is of a developing field with few concrete examples. The literature on climate adapted architecture includes assessments of bioclimatic designs and their potential resilience to future climate change (Nguyen & Reiter, 2017; Rubio-Bellido, Pulido-Arcas, & Cabeza-Lainez, 2015; Schilderman & Lyons, 2011). Otherwise, the literature is on potential design strategies, with a handful of articles that describe new design elements or technologies that can be used in larger adaptive strategies (Lomas & Ji, 2009).

3.2.1 Synergies

Some major works try to provide an overview of the subject at different points in time, discussing how to approach adaptations to climate change. Briller (Briller, 2013) made a comprehensive overview of approaches and strategies to address climate change in the built environment but never went into detail. His overview, however, does give a thorough walkthrough of the different strategies of adapting to the changing environment and how these interact with one another. Briller (2013) lists five points of adaptation to the changing climate that address the envelope, construction praxis, synergies, connection to the microclimate, and occupant behaviour. The basis of these strategies is simulation of the energy requirements in different climates within the United States. An important aspect of Briller's approach is the incorporation of the probabilistic nature of climate change, accepting that the changes could develop radically differently, and that solutions like continuous construction and occupancy behaviour are well argued and viable as design strategies for the future architecture. Briller (Briller, 2013) focuses mainly on preventing rising energy use as the climate changes. These measures are trying to circumvent overheating problems and the movement from a heating to a cooling climate, which is an issue faced in most temperate climates and which could create a demand for either electrical cooling or better opportunities for natural ventilation in future building design.

3.2.2 Adaptation in the building praxis

Gul & Menzies (2012) face the problematic probabilistic nature of climate change in their investigation on the willingness to implement building adaptations within building professions in the UK. While all parties agree that adaptation is important, they also agree that adaptations are expensive and those expenses could be better used elsewhere, which echoes Roders & Straub (2015) and their investigation into the willingness to implement adaptive measures in Dutch social housing. One trend noted in the literature is that adaptations need to have value beyond adapting to climate change; adaptations are expenses that can only show a benefit in the long term. Therefore, the adaptive designs must be of an immediate use or value to the user or owner (Arora & Saxena, 2009). Several articles mention that the devaluation of adaptive measures in building design, from the viewpoint of the building professional, and would prevent them from being implemented unless enacted through law (Gul & Menzies, 2012; Wilby, 2007). At the same time it would be difficult to settle specific laws for uncertain predictions such as the consequences of climate change (Gul & Menzies, 2012). Although frameworks are proposed (Zhao et al., 2015), a lack of political will and economy seem to be a blockade even in for at risk societies (Schilderman & Lyons, 2011; Sovacool et al., 2012). It is important to add that areas vulnerable to climate change have more unstable housing markets (Zhao et al., 2015). The problem with the probabilistic approach to climate change adaptation is approached by (Jenkins, Patidar, Banfill, & Gibson, 2014). They developed probabilistic tools that exemplify how the design for an uncertain future could be approached.

3.2.3 Hard and Soft Adaptation

Coley, Kershaw, & Eames (2012) define two kinds of adaptation—hard and soft. The hard are adaptations integrated in the design, which can be difficult or expensive to change during a building's lifetime. Soft adaptations can be changed or allow the occupants of the building to increase its resilience to climate change through easily accessible measures, e.g., openable windows and shades. Coley et al. (2012) reach the conclusion that user behaviour that interacts with soft adaptations might be as efficient as hard adaptations, but both strategies are needed to adapt buildings to the worst case scenarios. A similar conclusion with a larger focus on occupants is found in (Altomonte et al., 2015; Hatvani-Kovacs, Belusko, Skinner, Pockett, & Boland, 2016; J. Palmer et al., 2014; J. S. Palmer et al., 2013; Zuo et al., 2015)), whose argument is that sustainable architecture must be designed on the basis of human interaction. While the article mostly examines existing climates, it underlines the importance of user behaviour in making complex modern buildings work as intended. In (Stevenson, Baborska-Narozny, & Chatterton, 2016) the LILAC community in Leeds, UK, is used as a case study in resilience and sustainable living, and the article follows the development of the community in which occupants are the driving force in adapting to climate change. The design of the LILAC community is continually changed with input from the occupants who collect solutions to whatever problems arise and create a collective memory of the community and thereby increasing the resilience of the occupants as a whole. The design of the buildings was focused on resilience and adaptation through redundancy. Functions enhanced or synergized by other functions or backup systems can provide support for one another, thereby increasing both the resilience and adaptability of the building design. For example, the mechanical ventilation system was designed to be supported by natural ventilation if it were to break down or reach its capacity, and water collecting systems have alternating pump systems to keep them going at all times.

Investigating user vulnerability and adaptive capacity is the goal of Hatvani-Kovacs et al. (2016), the results of which are an overview of behavioural adaptations of people in different socio-economic situations. This is one of the few studies trying to approach this problem, and it focuses on the Australian context where the temperate climate faces worsening heat waves and warmer summers in the future.

3.2.4 Bioclimatic, Biomimicry and Regenerative design

Somewhat tangential to the (Stevenson et al., 2016) study of the LILAC community is the eco-systemic and open system model in architectural design, as described by (Du Plessis, 2012; Garcia-Holguera, Clark, Sprecher, & Gaskin, 2016; Gu & Evans, 2010; Pedersen Zari, 2015). The strategy in this model is to treat the building as an open thermodynamic system or ecosystem where the interrelated parts of the buildings interact not only with themselves but also with the surrounding environment. If designed correctly, the building can surpass the goal of sustainability and become regenerative, essentially bettering the natural environment the building inhabits rather than maintaining the current standard. Du Plessis (2012) criticizes the idea of resilience going back to a baseline instead of improving upon it. In regenerative design, the building is a net positive on its surroundings, which can prove useful, considering that floods could become a mainstay as a result of climate change and the buildings could act as a counter to the urban heat island effect. (Garcia-Holguera et al., 2016) use the Eastgate Centre in Harare as an example of an eco-mimetic design, and (Pedersen Zari, 2015) uses larger scale projects like the Kalundborg industrial park as examples of eco-systemic thought in design, where large scale industrial projects should set the precedent for smaller scale designs. One of the overarching problems with biomimetic design (exacerbated in eco systemic design) is the need for a scientific biological approach in identifying the organisms or systems suitable for mimicry. Problems arise if designs are made on assumptions of biological functionality rather than investigating the biology of the mimicked organisms. (Garcia-Holguera et al., 2016; López, Rubio, Martín, Ben Croxford, & Croxford, 2017; Yuan et al., 2017) both define methodologies that structure the workflow in bio mimicking design. Eco systemic and regenerative adaptations are mostly on a large scale at the moment (Pedersen Zari, 2015; Pedersen Zari & Zari, 2010), but future neighbourhoods could be designed as adaptive or regenerative networks with significant buildings acting as nodes (Pedersen Zari, 2015); this would require rethinking in the practice of local planning and governance to work, but could provide large positives for rainwater retention and heat management, while providing habitats that bolster biodiversity. Working with nature seems to have large benefits, since it creates buffers for floods and temperature increases while fostering the biodiversity of the area. In (van der Nat, Vellinga, Leemans, & van Slobbe, 2016) a ranking system for coastal protection measures is defined based on the utilization of natural barriers and protection and underlining the importance of existing landscapes and ecosystems in flood protection. Utilizing the ecosystem services that occur when fostering connections between urban and natural landscapes can be of enormous benefit (Knight & Riggs, 2010). The authors argue that through careful urban planning cities can become regenerative ecosystems on their own, if managed in a sustainable manner. They also argue that the division between the urban and non-urban landscapes should be broken down, and that cities could host functions like agriculture, which are currently based in the countryside.

3.2.5 Green Building elements

The most widespread adaptations to increased precipitation and flooding for buildings are the inclusion of green elements, either roofs or walls. While the walls may be less effective than anticipated (Riley, 2017), roofs can still play an important role in retaining rainwater, especially the intensive types, which are efficient and increase in efficiency over time (Speak, Rothwell, Lindley, & Smith, 2013). It is important to consider a planting strategy in green elements, not only to maximize the retaining capacities during the seasons when they are most useful (which for most oceanic climates will be winter) but also to retain biodiversity of the local areas in changing climates (Hunter, 2011). Choosing flowers and plants that thrive in the climate will both maximize the effect that they can have on the building, while minimizing maintenance. Resilient planting has the possibility to withstand the extremes of climate change, like droughts, as well. When designing green roofs, local rain patterns must be considered, the most problematic seasons identified, and whether the rain patterns are concentrated bursts or continuous downpours determined, an issue especially important in oceanic climates. The rain patterns in the Mediterranean climates as described by (Monteiro, Calheiros, Pimentel-Rodrigues, Silva-Afonso, & Castro, 2016) are continuous in nature while the oceanic climates are lean towards the winter season, hence water retention design must mirror this. This division in the oceanic climates will only grow stronger due to climate change, less rain overall but more in wintertime (IPCC, 2014). The species used in urban planting should also be considered carefully since some species of trees might actually contribute to air pollution through volatile organic compounds (VOCs), the production of which is linked to heat and solar radiation, a problem that will only increase with climate change (Wilby, 2007).

3.2.6 Flexibility, Mobility and Reaction

In response to flooding and coastal erosion, Angus D. Gordon (Gordon, 2013) proposed building for change, simplifying the infrastructure in such a way that it will be easy to disassemble and relocate as water levels rise. Buildings could also change with the users and potentially serve as material banks in a circular economy if they could be disassembled (Geldermans, 2016). A less radical solution is found in Edelman, Vihola, Laak, & Annila (Edelman, Vihola, Laak, & Annila, 2016), which discusses the use of prefabricated schools and day-cares that can be built and disassembled easily, and investigates the architectural value of these buildings for users. Lack of integration with the site and rough aesthetics often lead to dissatisfied users in mobile buildings. English, Klink, & Turner (2016) examine amphibious architecture, a relevant road of adaptation to increasing flood events. Amphibious architecture allows adapted buildings to work like normal buildings and only rise when flooding occurs; horizontal movement is restricted by columns along which the buildings slide vertically. Amphibious buildings are better connected to the context, more accessible and less vulnerable to wind than elevated buildings, which is the immediate alternative. Amphibious buildings do not translate well into large scale and heavy constructions, which limits design choices and may lead to lower energy performance. Plumbing must be designed to disconnect with ease during floods, otherwise the building could suffer further damage and be a cause of contamination in the floodwater. Many of the solutions mentioned are being used in disaster zones with resilient buildings that are easy to assemble and disassemble (Murgul et al., 2016).

3.2.7 Passive and Active Design in response to overheating.

Hacker & Holmes (2007) simulate the future climate and its consequence on different building typologies, which are archetypes from the late 20th century. The article assesses their viability in a changing climate and how they perform with implementation of adaptive measures. The authors argue that the biological adaptations of humans to the average temperatures of their environment should be accounted for, which means that humans should become more tolerant to heat as average temperatures rise, and this may lower future cooling needs. Even with biology taken into account, the authors argue that prevention of overheating resulting from climate change within buildings is required. Overheating can be solved in active or passive ways. Active solutions, such as air-conditioning, are the easiest to install in existing buildings, but have high-energy demand and will generate more heat on the exterior contributing further to urban heat island effects. Passive solutions are a preferable way to deal with future overheating issues but must be implemented in the architecture from the beginning in order for their full potential to be utilized. Newer studies like (Hamdy, Carlucci, Hoes, & Hensen, 2017) reach the conclusion that in Dutch housing most of the cooling needs could be covered by mechanical cooling, and they affirm that newer energy efficient buildings are most vulnerable to overheating. The simulations of (Moazami, Carlucci, Causone, & Pagliano, 2016) repeat this, showing the effect of energy retrofits in day-care centres under morphed climatic data. The buildings will save energy in the short- to mid-term, but savings will be negated later by cooling demands.

Buchin et al.(Buchin et al., 2016) reach a similar conclusion, although they argue for minimizing the lethality of the increasing heatwaves in the future, which leaves active cooling a viable strategy if used thoughtfully, e.g., by creating strategically cooled rooms in care facilities. They argue that green elements in buildings have little cooling effect outside the bounds of their immediate vicinity, and contribute little to reducing the urban heat island effect, which contributes to heat waves in urban environments. This is counter to what many simulations studies use as their basis (Iyengar et al., 2012). Buchin et al.(Buchin et al., 2016) find that the most efficient passive architectural adaptations to heat waves are urban trees and reflective surfaces. While air-conditioning is an efficient interior adaptation, the greenhouse gas emissions it produces makes it less useful, since mitigation of climate change is still important in the built environment.

In Palmer et al. (J. Palmer et al., 2014; J. S. Palmer et al., 2013) and Zuo et al. (Zuo et al., 2015) alternatives to mechanical cooling are discussed with a focus on *cool retreats*, rooms that are easy to cool that residents can inhabit during severe heat waves. The articles examine and simulate typical building cases in subtropical regions, and both their original design and designs with either adaptive changes or cool retreats are tested. The retreat proves to be efficient at minimizing power use during the heat waves, and the most efficient retreats are those placed underground, but converted living rooms on the ground floor also prove efficient. Similar to Palmer's cool retreat (Amoako-Attah & B-Jahromi, 2016) test solar conservatories as adaptive and energy saving measures, which work in the simulations, but Scandinavian studies show that these savings are negated by inhabitants' behaviour (Marsh, 2017). Advanced natural ventilation systems like those proposed in (Lomas & Ji, 2009) might play a more important role in future building designs and act as substitutes for AC in oceanic climates. Envelope design solutions that respond passively or actively to a changing environment are going to be key, but the general discussion is whether to use active high tech mechanical solutions (Luther & Altomonte, 2012; Pan & Jeng, 2012) or passive low tech (Holstov, Bridgens, & Farmer, 2015; Holstov, Farmer, & Bridgens, 2017; Laver, Clifford, & Vollen, 2008; López, Rubio, Martín, & Croxford, 2017; Luther & Altomonte, 2012). The passive designs often benefit from biomimicry, especially from plants, since they have evolved to their climate's light, temperature and moisture, which are the same factors that are important to effective building envelope functions (Holstov et al., 2015, 2017; Laver et al., 2008; López, Rubio, Martín, & Croxford, 2017; Yuan et al., 2017). Again the design strategies in the façade should be something the user can interact and relate to (Arora & Saxena, 2009) before they increase a building's adaptive capacity.

3.2.8 Threat of overheating

Pathan et. al provide a review of comprehensive measurements of temperatures taken in 122 homes in London during the summers of 2009 and 2010. The researchers give an overview of which building typologies were exposed to overheating and heat waves. It was found that all buildings suffered from overheating during the summer, particularly in the bedrooms. The most vulnerable buildings are newer sustainable buildings, which have a small coping range before they overheat because energy saving measures do not allow them to cool off at night. The study is not without flaws, however. During the two summers in which the houses were measured similar outdoor temperatures were recorded, which would lead one to expect that the indoor measurements would be similar as well. However, Pathan et al.(2016) describe large differences in measurements, from either the use of imprecise equipment or, more realistically, the result of occupancy behaviour. The study does not include occupancy observation or interviews and therefore the relation between behaviour and indoor temperatures is not investigated. As this has been shown by (Altomonte et al., 2015; Hansen et al., 2013; Stevenson et al., 2016) to have an impact, the integrity of the study loses some of its lustre.

Coley & Kershaw (Coley & Kershaw, 2010) reached similar results in their simulations, finding a linear connection between the temperature within buildings and the outdoor temperature—the major point of differentiation being building typologies. The authors argue that the architecture of the buildings is the primary concern in issues of overheating, although this is based on the assumed behaviours of the occupants.

Problems with overheating are explored by (Vardoulakis et al., 2015), who conclude that health issues associated with overheating and poor indoor climates are problematic, but that there is a lack of information on how outdoor temperatures relate to health issues in building interiors. They argue that it is important, therefore, to adapt both new and existing buildings to rising temperatures.

3.2.9 Holistic Adaptation

Vardoulakis et al. (2015) argue that consequences of climate change should be considered in a holistic manner. This could mean, however, that solutions to one problem could be maladapted to the full range of climate change's effects, for instance, water retention systems could become breeding grounds for pests or bacteria in a warming climate. They also discuss flooding's effect on inhabitants' health and adaptations, either through "wet" or "dry" adaptations. "Wet" adaptations ensure that constructions can handle flooding without damage and health hazards (like mould), whereas "dry" adaptations prevent buildings from flooding. This exposes another vulnerability in sustainable architecture, which is that their constructions can be very vulnerable to water, and "wet" adaptations are therefore not advisable. Likewise, it is important to consider insulation types, since organic insulation is prone to rot if exposed to moisture. To prevent damage in building envelopes from flooding, treatments can be applied to the surfaces to prevent ingress of water (in masonry, at least). The level of craftsmanship in the construction may be as important as the materials used (Beddoes & Booth, 2015).

4. DISCUSSION

This review is based on an iterative search method, which was chosen in order to highlight certain interest points within a wide and multidisciplinary field of literature on an informed basis. The goal was to create a series of narrow searches that could minimize manual sorting, which would be required of less specific search methods. The idea was that the iterative process between each function would focus the review towards meaningful subjects for the overarching article.

This approach contains pitfalls, but these were alleviated through multidirectional entrances to the subject. A major pitfall was whether the keywords would correspond to the terms used in articles discussing architecture. Therefore, articles needed to contain either a variation of the term *architecture* or *building* and *design* to narrow the searches to articles approaching architecture as its main subject in relation to climate change. Likewise, one should be aware that the field of architectural scientific literature lacks uniformity in terminology. In the case of adaptive architecture, the term describes any architecture responding to change. This also applies to the field of architecture as an offset for discussing climate change, as the review is confined within the field of architecture and building sciences, the environmental sciences underlying the theory of climate change and its effect on the local climates could have been better investigated, although that would necessitate a far wider and resource consuming review.

The process was shaped by the first search since the result of this would lead to the next, so the starting point shaped the progress of the search. Nevertheless, it did lead to related searches that were not immediately obvious, and which benefitted the review as a whole.

5. CONCLUSIONS

Further research must be directed not only toward taking the changing climate into account but also seeing buildings as elements of a larger man-made ecosystem, adapting to the changing climate not only by themselves but as a net positive in their context. Here runoff is relevant, since runoff produced from human habitation creates problems not just within cities but also in the surrounding nature. It is important to question the meaningless distinction between natural and manmade landscape; they mutually affect one another. New buildings should strive for co-habitation and regeneration, integrating the users in the long-term use of the buildings through easy to use design and rehabilitating the natural systems they interact with.

To reach these goals is it important that adaptations to climate change within architecture are meaningful for builders, owners and users; otherwise, adaptations might never be implemented. Studies into why and how home owners and organizations build and renovate support this (Fyhn & Baron, 2017; Gul & Menzies, 2012; Kunreuther & Weber, 2014; Roders & Straub, 2015). It is not enough to integrate adaptation in architecture; the architecture must support the users in their individual adaptations and offer them an adaptive choice—something that may be absent in modern sustainable housing, which is often reliant on high-tech machinery to condition the interior spaces, and which is particularly sensitive to the impacts of climate change. The design of the adaptive measures could be designed intuitively for the users who not wish to know about the technical intricacies of the adaptive systems.

Ideally, future research should approach climate-adapted architecture from a holistic perspective. It should focus on an integrated implementation of the different technologies and methods that can mitigate the impact of climate change in the buildings.

The focus must include residential buildings, since this is where people in western societies spend most of their time, and where there are the greatest vulnerabilities to climate change, whether the floods destroying homes and driving insurance pricing up or the heat waves threatening the health and wellbeing of the residents. Functionality should follow the rhythms of the homeowner and it is therefore extremely important that the behaviours of the users are understood in regard to adaptive technologies. While it is not possible to test user behaviour in future environments, it may be useful to get a comprehensive overview of user behaviour in regard to current extreme weather events in residential architecture through observations, case-studies, and interviews. This could prove valuable both in research and future building design and validate or discard certain adaptive solutions based on user interaction. The research could be performed across cultures sharing the same climate, to gain an understanding of how the culture of the inhabitants might play a role in their interaction with adaptive measures.

One of the major issues with climate change is that it is defined by the local climate; therefore, one overarching solution will never be viable everywhere. Rather, the benefits and potential synergies in design solutions should be investigated and evaluated within ranges of adaptive capacity that could mitigate different levels of climate change. The adaptive capacity of the residents should be considered in the architecture since they can create adaptive buffers towards the extremes of climate change.

Further research should focus on how to not only make the buildings adaptive but also regenerative in their surrounding environment, whether natural or manmade. This could enable new buildings to mitigate some of the climate change impacts, which could help the building adjust to a new climate. It could also provide valuable benefits to biodiversity, groundwater recharge, air quality and human comfort, which goes beyond the goals of adapting to climate change.

It would be beneficial to build upon this review by defining concrete design strategies for climate change adapted architecture.

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