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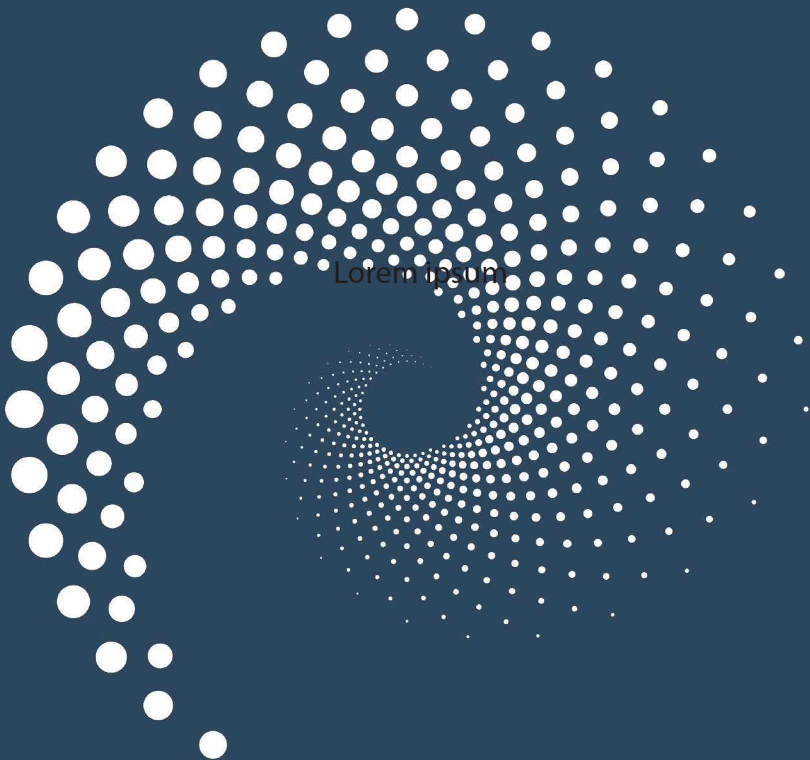
FROM MEGA TO NANO
THE COMPLEXITY OF A MULTISCALAR PROJECT



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Francesca Scalisi

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4

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Volume 4

Edited by Francesca Scalisi

FROM MEGA TO NANO: THE COMPLEXITY OF A MULTISCALAR PROJECT

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INTRODUCTION

The present book collects essays, studies, research and projects on the subject entitled 'From Mega to Nano: the Complexity of a Multiscalar Project', inextricably linked to the ever-increasing request of trans and multidisciplinarity of the project. The ability of 'change of scales', work on more different scales – multiscalarity – create new ones or change the meaning of the scales commonly accepted, it is common practice in the approach to the project and has always concerned architects, engineers, designers and artists for the multiple symbolic and real meanings of the size of a territory, a city, an architecture and an object. However, it can provide a range of opportunities even in different contexts such as economy, politics, culture, etc.

The concepts of scale and size are fundamental to link, in a systemic point of view, the detail with the big picture, the detail with the group, to interpret and represent, to discretize and recompose elements and parts that stand in a hierarchy or interconnection relation, to investigate the physical and social, to outline critical issues and potential, but especially to establish the importance of relational aspects between the group and its component as a way to understand their identity, their nature and organization, their regulation rules and the role played in different contexts, namely the fundamental elements to identify the form and structure of a territory, a city, an architecture and an object.

The concept of scale in Architecture regulates the size of the anthropic space, always keeping human dimension as reference. The choice of the scale inevitably becomes a conceptual selection of what the project actually wants to represent. When using multiscalar representation, we try to show the complexity of reality, by using as many regulation criteria and specific evaluations as we can, not only by describing its size and geometric aspects but most of all by significantly highlighting its qualitative aspects and those related to identity, culture and history. This means that there is not just one scale to represent a territory, a city, architecture, an object or a detail; however, in terms of a necessary multiscalarity, the project chooses the most fitting scale to develop practices, on a case-by-case basis. Therefore, logically the scale influences the project: thanks to the progress of technology in the field of design at all levels, it is probably the component of the project on which the designer works the most, simultaneously coordinating real and virtual relations; these relations do not end when the form is created, but continue over time and modify the management of the object's complexity.

The papers in this volume, dealing with many disciplines, should be read in this sense. The essay written by Nicola Campanile entitled 'The appropriate form – The analogy between the architectural and urban scale' gives a reasoned point of view in the architectural field on the concept of multiscalarity and its operational implications in the architectural project, trying to carry out a resemantization operation while relating this concept to the subject of analogy, a conceptual operation supported by the analysis of Aldo Rossi's architecture which, in relation to the subject, can be considered paradigmatic.

Another key to understanding the subject is given by Ermelinda Di Chiara that in 'The City of Agrigento – The form and the space of the city: an interscalar approach' sees in the interscalar approach to the project a dimension and an operational principle through which it is possible to know the territory and its relations with urban systems in order to understand its principles, nature, organization and the role it plays in different contexts. The concept of interscalarity is explained through the case study of Agrigento, analysed from an 'oversized' dimension (the temples) to the infinitely small (the houses).

Next, Bianca Andaloro presents a paper entitled 'Multiscalarity of adaptive architecture – The efficiency of micro and the resilience of macro in contemporary design'. It investigates the relation between the efficiency of micro and the resilience of macro in contemporary design starting by questioning which type of architecture is willing to welcome a constant comparison between different scales, materials and practices. Through the study of three recent projects, emblematic for their spatial and systemic complexity (Hardingham's Generator, Carlo Ratti Associati's Currie Park, and Reset), the essay identifies resilient architecture as the type capable of elaborating innovative characters through adaptive processes. The paper suggests that, in managing the complexity presented by an adaptive approach working in the interrelation between elements of different scales, an important role can be played at the micro-scale by the technological components which, added into the building and working at the medium scale, can capture information from an external base and return a response to improve environmental conditions and human needs.

Also, the paper written by the editor of this volume deals with the compelling environmental issue and the concept of adaptiveness, since it investigates the relation between Adaptive Facade and Phase Change Materials (PCMs) as a new paradigm for a sustainable approach in the building industry. The researchers and designers currently focus on new types of envelopes characterized by dynamism, adaptiveness, smart control, responsiveness, integration-hybridization, biomimicry, etc., fostering new subsystems not intended anymore as elements opposing to a flow, but – on the contrary – as 'filters' (between different scales) that receive by controlling, or oppose in a 'smart' way to, the external weather stresses by intercepting and capturing them in different directions depending on the seasons and the exposures, therefore assimilating the frontier envelope to a 'technological Janus'. In this research context, the paper focuses on the characteristics and potentialities of

Phase Change Materials (PCMs) that change to 'answer' to temperature variations, changing their state, from solid to liquid and vice versa, depending on the amount of heat they absorb. In particular, it highlights the characteristics, advantages, limits, and fields of application of PCMs, focusing specifically on current research and future scenarios, mostly in relation to the contribution given by nanotechnology to boost the property of these materials used in the building industry.

The paper entitled 'Climate risk management in the big data era – A multiscale, multidisciplinary and integrated approach' by Maria Fabrizia Clemente highlights that in Architecture the research is pushing towards the integration of quantitative variables to support decision making processes. The introduction of enabling technologies and the dissemination of big data have enriched the projects with new inputs, but their added value lies more in the ability to extract, analyse and interpret the requested information through a multiscalar, multidisciplinary and integrated approach, rather than in the volume that characterizes these data. In the context of climate risk management to support resilience projects, plans and policies, the acquisition and processing of an increasing amount of information is required to understand the complexity both of the territories and of natural events; however, there is a gap between the complexity of the models and the abilities of the users. Among the different natural phenomena, the paper focuses on flooding, one of the most complex and dynamic phenomena.

Francesca Albani and Matteo Gambaro in the essay 'Multiscalar approaches to re-appropriating the Visconti-Sforza Castle in Novara between conservation and reuse' describe the case of the Castle of Novara. In this case study, even with some outstanding issues, the multiscalar and cross-disciplinary approach of the process has led to its re-appropriation to the city and it has become emblematic for the definition of new strategies for Cultural Assets which represent an important cultural and economic resource. To preserve the marks of their transformations and ageing represent the will of the modern city to take back the many 'stories' that these places can tell, enjoying them and making them part of the urban dynamics of a community that has been waiting for too long an answer to these issues.

Roula El-Khoury Fayad and Silvia Mazzetto in 'Nation-building macro-narratives from Lebanon and Kuwait – The journey of Sami Abdul Baki' report about the Golden Age, between the 1950s and 1960s, in Lebanon, when talented Lebanese architects having studied architecture abroad came back and made numerous successful collaborations between local and foreign architects; and in Kuwait where it has represented an interesting experimental ground for testing new ideas, projects and building techniques, together with the contributions of Western architects. Although the story of the modern architectural development of these two countries has been mainly characterized by great narratives, other works made by professionals who are not members of the dominant culture have made an important contribution. This is the case of Sami Abdul Baki designer of eclectic architectures in significant places both in Lebanon and Kuwait, author of parallel micro-narratives that can contribute to a better understanding of the complex context of the two countries.

Then, Paolo Carli, Roberto Giordano, Elena Montacchini and Silvia Tedesco present the research entitled 'Experiential tourism – Research, experimentation and innovation' carried out at Alta Scuola Politecnica in collaboration with the industry, whose objective is to simultaneously carry out research and teaching by experimenting and prototyping new solutions and answers to real tourism problems and its most recent evolution: 'experiential tourism'. Highlighting the potential of a multiscalar approach used as a tool to handle complexity, through a specific experimentation the paper leads the way both to ensure the quality of higher education and research activities in universities, at the same time committing to achieve its application, and to promote the ability to enhance the intersecting between supply and demand for innovative knowledge and technologies.

Paolo Di Nardo and Alessandro Spennato in 'Design(ing) – The multiscalar project', through a series of emblematic case studies, refer that the research of a new way of understanding the contemporary creative and scientific project does not begin with – as it was in the past – the demolition of already defined and experimented works, but it aims to establish precisely on such research an ideation path capable of grafting contemporary elements onto an already structured knowledge. Therefore, it should not be chosen, for example, technology alone as a solution to renewal, but all those contemporary requests – including the sustainable aspect to respond to the climate crisis – that know how to update multiscalar and multidisciplinary knowledge.

The volume ends with a paper by Daniela Anna Calabi and Elisa Strada entitled 'Design of the atmospheres and the narrative dimensions – Literary Writing and Visual Writing' which reports a translation experimentation from text to images to prove that the atmospheres related to the narrated space can be a guide to the territories and can transform into visual experiential text, an 'atmospheric text'. In the atmospheric texts it is possible to trace two connotations: one concerning the style that characterizes the image and which relates to the choices made by the author; the other concerning the recognition of stereotypes so that an image, associated with an oral text, can determine the attribution of a meaning increasing that of the source text. The final result is a design increasing the editorial text experience, but also the understanding and hence the identity of narrated spaces.

In conclusion, the essays and research published show that if measuring, using the scale as a tool, means understanding the things in the world by establishing some differences, therefore 'off-size' can be the basis for new theoretical assumptions in which both the infinitely large (mega) and the infinitely small (nano) contribute to defining crucial topics, such as environmental, social and economic sustainability, resilience, territory government, the idea of space, aesthetics, use, development of new products, services and materials, etc. Therefore, the multiscalar approach can be considered as an important design working tool that, in a systemic point of view, can foster the proposal of adequate strategies for action and planning of sustainable actions, developing new methods, working techniques and shared measurements, through well-considered hierarchies of priorities necessary to optimize the choices of the project and to determine the reliable cost/benefit balances (especially of environmental nature).

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ADAPTIVE FACADE AND PHASE CHANGE MATERIALS (PCMs) A sustainable approach for building materials

Francesca Scalisi

section
ARCHITECTURE

typology
ESSAYS & VIEWPOINT

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ABSTRACT
In the building industry, the building envelope can be crucial to reduce energy consumption and CO_2 emissions in the atmosphere, contributing – with adequate technical and technological solutions and energy-efficient materials – to a prospective energy saving that the European Union estimates at 32.5% by 2030. Creating ‘adaptive’ envelopes in highly energy efficient buildings is an already available option, with thanks to some materials such as Phase Change Materials (PCMs), developed by the research at ‘micro’ and ‘nano’ scales. PCMs give the possibility of reducing the daily fluctuations of the room temperatures through the reduction of indoor temperature peaks. This paper highlights the characteristics, advantages and limits of PCMs, focusing in particular on current research and future scenarios, mostly in relation to the contribution given by nanotechnology to boost the property of these materials used in the building industry.

KEYWORDS
adaptive facade, phase change materials (PCMs), thermal energy storage (TES), nanotechnology, sustainability

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By 2030, the planet we live in will be different: Thomas L. Friedman (2016) observed that the three main forces of our Planet – Moore's Law (technology), the Market (globalization) and Mother Nature (climate change and biodiversity loss) – are all pressing at the same time, with inevitable consequences for territories, cities and buildings that will be designed and created in the future. The 17 2030 Sustainable Development Goals presented by the United Nations (2015) provide an important answer to this time horizon, tracing the path towards a development model for a better and more sustainable future for everyone. But will these Goals be able to accelerate sustainable innovation? However, it is clear that how our planet, its landscapes, cities and architectures will be in the future will mostly depend on the decisions we make today, on our level of 'vision', on how the research will evolve and on how we will deal with the subject of sustainability with respect to the aforementioned Goals.

Going beyond 2030, imagining 2050, according to the United Nations (2019) we will have to deal with a population growth, it will reach ten billion people, 75% of which will be concentrated in cities and urban areas; and if the cities of the future become crucial metropolises for the sustainability of the whole planet, the population increase will determine a greater demand for energy and higher CO_2 emissions in the atmosphere, which have already increased in the last 20 years respectively by 49% and 43% (IEA, 2019a). Other data require some considerations: in 2018 the building industry has absorbed 36% of global energy consumption and produced 39% of annual greenhouse gas emissions. These data surely are very alarming, but are nothing compared to the 2050 outlook, when the energy demand will increase by about 50% and the demand for building cooling will triple compared to 2010 values (IEA, 2019b).

In response to the rise of Earth's temperature, there are many recommendations suggested by international non-profit Bodies and Organizations: to dynamically respond to ongoing change processes and the effects caused by exogenous or endogenous distresses such as climate change and the progressive shortage of resources (EC, 2017), and also to increase the resilience and ability to adapt to the climate, together with ecosystem quality and the overall environmental performance aimed primarily at climate mitigation, CO_2 reduction and energy efficiency, starting from urban and environmental redevelopment and regeneration projects, to be implemented following the Green City Approach (OECD, 2016).

In the building industry, the building envelope can be a crucial building subsystem to reduce energy consumption and CO_2 emissions in the atmosphere, contributing – with adequate technical and technological solutions and highly energy efficient materials – to a prospective energy saving that the European Union estimates at 32.5% by 2030 (European Parliament and The Council of the European Union, 2012, 2018). The strategic role of the building envelope is also confirmed by the Global Alliance for Buildings and Construction (IEA, 2019a). It reports, among the various actions to be implemented (strategies, construction techniques and resilient materials), also the creation of adaptive envelopes useful to overcome the progressive limitation and non-renewability of natural resources and to create buildings with high energy efficiency and low CO_2 emissions, allowing to contain, on the one hand, the increase in the average global temperature well below 2 °C compared to pre-industrial levels, and on the other, the growing energy demand for cooling. These guidelines must certainly be coupled with adequate policies that the countries will have to implement and the dissemination of best practices in which heating and cooling are regulated by adaptive and 'passive' envelopes (Tucci et alii, 2019).

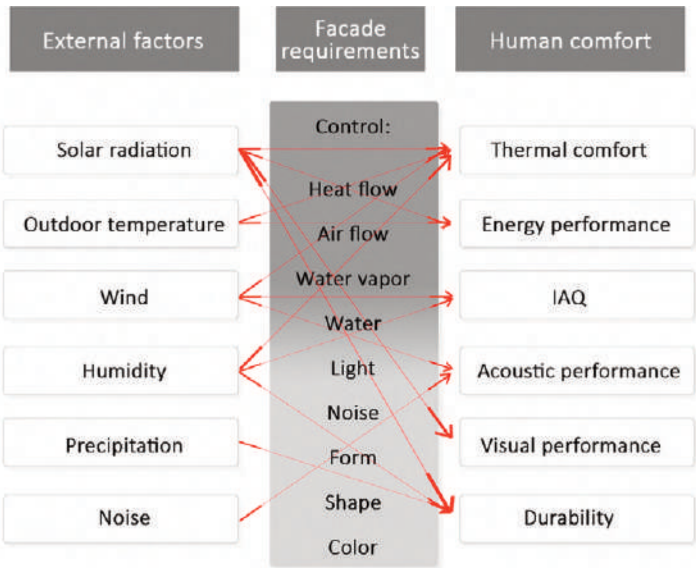
In the light of these premises, the paper, after having highlighted the importance of 'adaptive' envelopes as a possible solution to the environmental issues, focuses on the characteristics and potentialities of Phase Change Materials (PCMs) that change to 'answer' temperature variations, changing their state, from solid to liquid and vice versa, depending on the amount of heat they absorb. In particular, the paper will highlight the advantages, limits and fields of application of PCMs, as documented in reference scientific literature, especially in relation to the research carried out at micro and nano scales to enhance the properties of PCMs to be used in the building industry.

A new paradigm: the facades, from envelope to osmotic and adaptive membrane | In the second half of the 20th century, architecture has experienced a period of extreme linguistic, aesthetic and semantic, as well as technical, innovation thanks to the introduction of technologies that have allowed the creation of self-supporting domes, remarkable overhanging bodies or volumes with particularly complex geometries, but also the use of metal surfaces and plastic materials in building envelopes. This was possible with thanks to new building techniques and innovative digitization processes. In many of the above-mentioned architecture elements we can find a will to express a 'semanticity' that goes beyond the other expressive and technological 'constants', to create 'living-spaces', no more linked to a vision based on 'normal' three-dimensionality, but multiplied by points of view that often deviate from any pre-existing model and from what is the normal human 'perception' (Dorfles, 2007), to communicate a more marking than stylistic value, to take on the role of 'symbol-buildings' (to mention two well-known examples: Agbar Tower in Barcelona by Foster and the Guggenheim Museum in Bilbao by Gehry) having two essential characteristics: they are 'marks' in the urban confusion that surrounds them; and also to replace the 'modest' monuments of the past (Dorfles, 2007).

This great attention given to formal and aesthetic issues has led architects to often neglect the energy performance of the envelopes and the potential benefits they could have provided to the environmental issue (Addington, 2009), delegating to 'active' systems the air heating, ventilation and cooling necessary to compensate for the indoor thermohygrometric conditions caused by the indiscriminate use of large glass surfaces.

Starting from the mid-1990s, the gradual awareness on the environmental emergency (and of the repercussions in human, social and economic terms) reverberating on buildings through 'macro phenomena stressing the whole building system', the growing cost of energy and the demand for a higher-quality thermohygrometric well-being made by the users have pushed the researchers and designers towards new envelope concepts in general and facades in particular, accelerating innovative practices with new approaches characterized by dynamism, adaptiveness, smart control, responsiveness, integration-hybridization, biomimicry, etc., fostering a new paradigm (Perino and Serra, 2015). In this paradigm, these sub-systems are not intended anymore as elements opposing to a flow, but – on the contrary – as 'filters' (Favoino et alii, 2014) that receive by controlling, or oppose in a 'smart' way to, the external weather stresses by intercepting and capturing them in different directions depending on the seasons and the exposures (Addington and Schodek, 2005), therefore assimilating the frontier envelope to a 'technological Janus' (Lucarelli et alii, 2020; Tab. 1).

The 'mitigation' strategy, among the strategies identified to respond to these solicitations, is consolidated, but many experiments and recent achievements suggest the need for it to be coupled with an 'adaptation' strategy, using a range of 'adaptive solutions' involving the 'micro' scale (Lucarelli, 2018) through the use of components (often derived from transfer of technology) capable of providing increasingly extreme performance responses to external stresses (in terms of indoor comfort) with low energy consumption, or the 'nano' scale with materials already used in the first biomimetic applications in envelope systems. The resilient attitude of biological systems to respond in an adaptive, reactive and dynamic way to hostile and adverse external stresses, aiming to minimize the system's vulnerability rather than safeguard the full integrity of the system at all costs – that is, to ensure that it can preserve its vital functions with minimal



Tab. 1 | Schematic role of adaptive facade (source: Aelenei, Aelenei and Vieira, 2016).

losses (Belpoliti, 2013) – it starts to interest the building industry since it is so effective and efficient that it aims to be a new paradigm from which draw inspiration to design the functioning of artificial systems (Benyus, 1997).

In this sense, the aim of the project goes beyond the configuration optimization of the object following specific conditions – expected, static or predictable within a limited range of variation – favouring resilient behaviours throughout their whole service life answering variable environmental stresses (Antonini, 2019) to be implemented with an adaptive and dynamic attitude, and through a range of progressive tactics and actions, proportionate to the stress (Oguntona and Aigbavboa, 2017). Some examples of resilient facades are: 'dynamic' envelopes, which control the relation between the external environment and the building by managing the different energy flows through integrated systems (materials and components) capable of changing their shape, alternating functions and organizing spaces (Pesenti et alii, 2015; Luible and Overend, 2018); 'smart' envelopes capable of improving the energetic and environmental management with sensors and built-in actuators connected through the devices of the IoT thanks to the real-time analysis of data on the operating conditions of the envelope (Arnesano et alii 2019) and by 'biomimetic' envelopes that, by mimicking animals and plants nature as 'model, measure and mentor' (Benyus, 1997) and learning from its behavioural and performance paradigms, use only techniques and technologies, materials and components that react to environmental stimuli in an 'organic' and 'passive' way (Tucci, 2017). Even with their relative peculiarities, all the aforementioned types of envelope can be included in the 'adaptive' envelope category, defined by the EU COST Action TU 1403 Adaptive Facades Network (Luible, 2015) as closing systems made up by multifunctional (preferably 'passive') and highly adaptive systems capable of changing their functions, characteristics, properties, performances, configurations or behaviours in a fixed period of time, responding to variable boundary conditions and with the aim of improving the overall performance of the building.

The most common solution is to integrate mobile devices into the artifacts, although the environmental issue should lead us to rethink the use of large motor-powered and energy-intensive elements and to think on the complexity of these systems also in relation to building and maintenance costs. In this respect, some examples are the Institut du Monde Arabe, designed by Jean Nouvel in 1987 in Paris, in which the 30,000 metal diaphragms inspired by the mashrabiya are moved by engines managed by a central computer and require constant maintenance due to frequent mechanical failures; or the Al Bahar Tower in Dubai, built in 2012 with a project by Aedas and ARUP in which the structural elements of the adaptive facade will reach physical obsolescence in the fiftieth year of their operation and the many components that make it move (such as actuators and bearings) will not last more than fifteen years (Karanouh and Kerber, 2015).

Therefore, the research is oriented towards biomimetic applications emulating, through materials designed at a 'micro' and 'nano' scale, the behaviour of living organisms originating a functional, morphological variability of the objects concerned, and

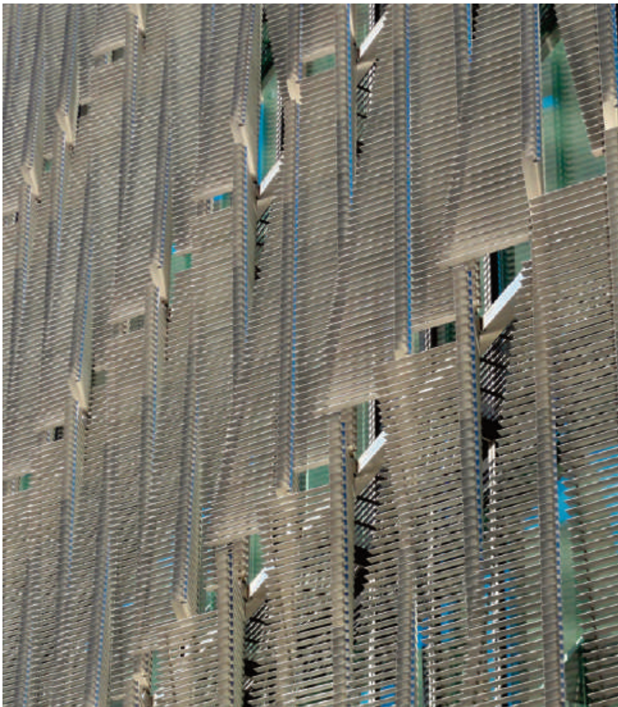


Fig. 1 | Q1 – Thyssenkrupp Quartier, JSWD Architekten, 2010, Essen Germany (credits: www.jswd-architekten.de/projekte/thyssenkrupp-quartier/).

Fig. 2 | Shiver House designed by NEON: a kinetic 'animal like' structure which moves and adapts in response to surrounding natural forces, Korppoo, Finland, 2019 (credits: www.neon.uk/?utm_medium=website&utm_source=archdaily.com#/shiver-house/).

Fig. 3 | Al Bahr Towers, Abu Dhabi, 2012 (credits: www.arup.com; www.re-thinkingthefuture.com).

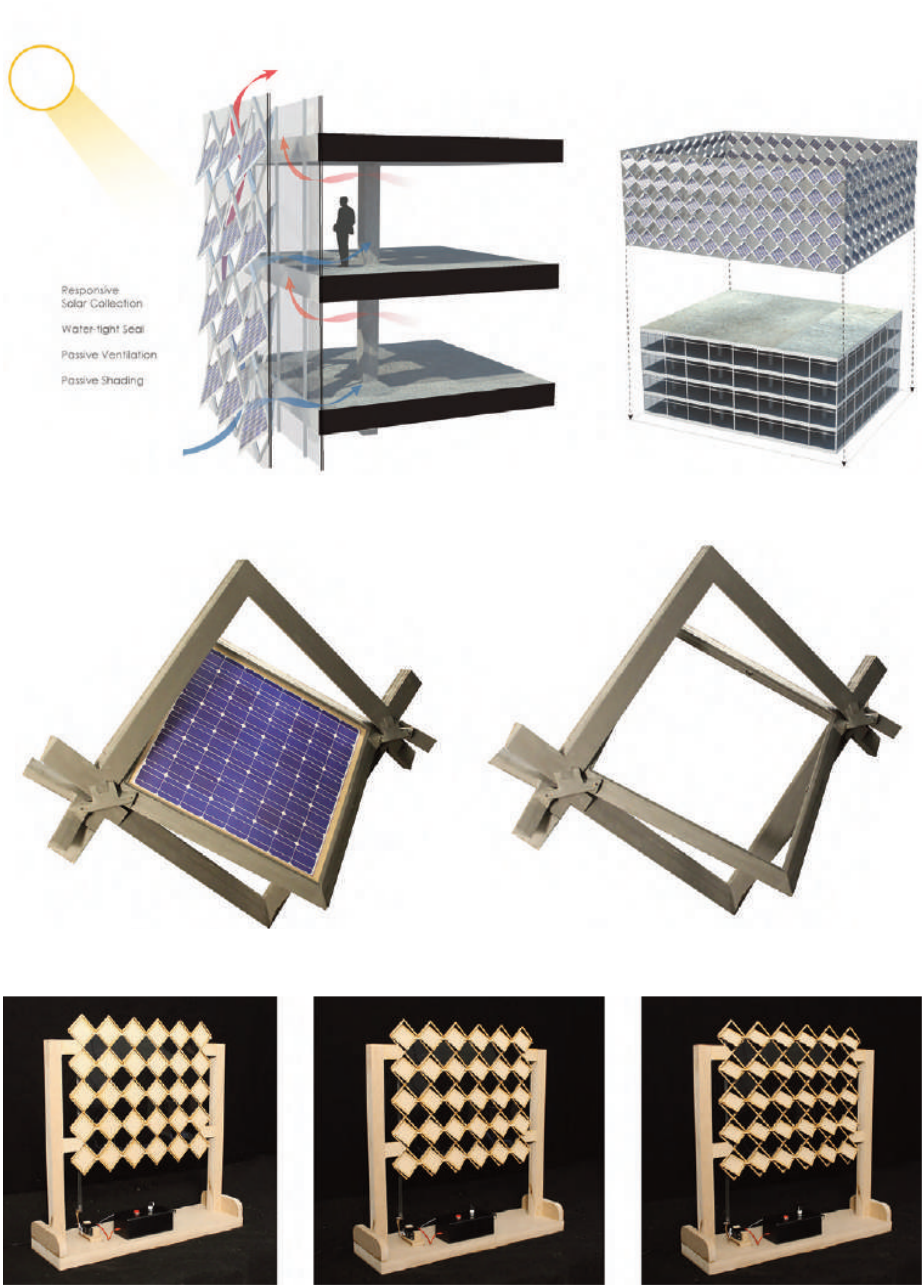
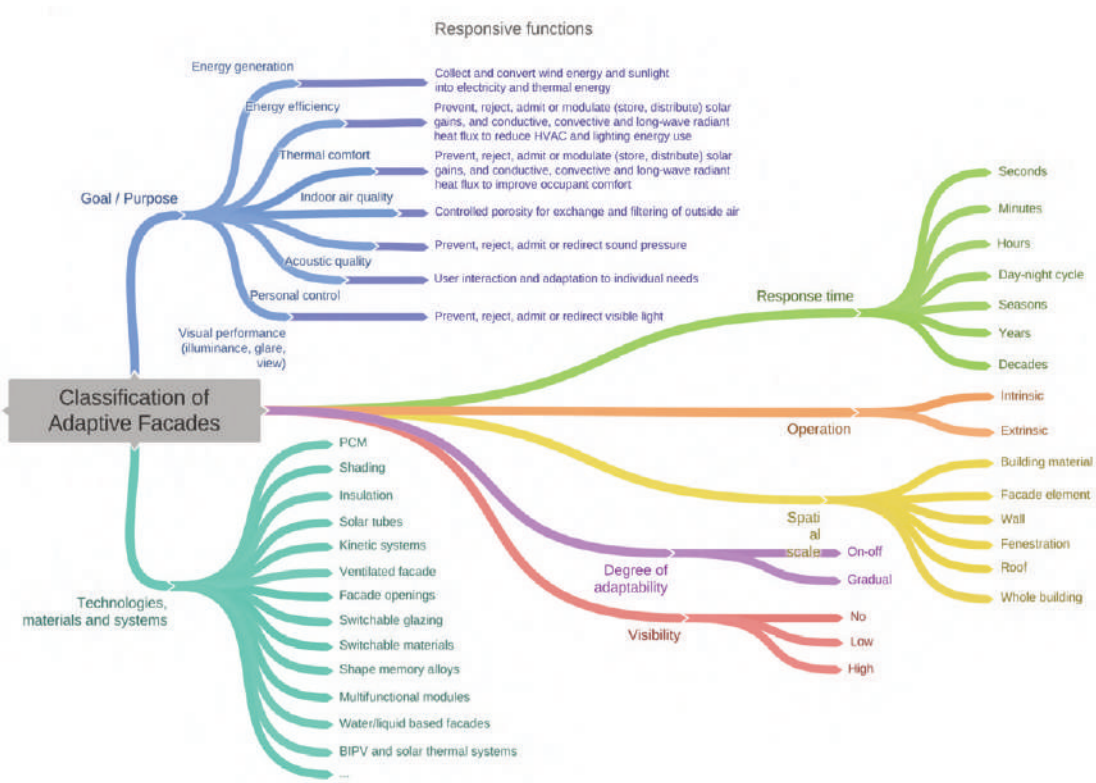


Fig. 4 | Adaptive Sola Skin, self-supporting solar collection façade: prototype with removable panel (credits: danielraznick.com/about/adaptive-solar-skin/).

often also to their appearance (Persiani, 2019). Consequently, the dynamism is no more linked to the action of a mechanic actuator hidden from view but, for example, to photochromic coatings that regulate glass transparency, or to brise-soleil moved by phase-change actuators or even to external coating membranes that change their geometry and volumes, according to the incident solar radiation on surfaces (Wayne, Santoso Mintorogo and Sigit Arifin, 2019; Figg. 1-4).

Regardless of the type of adaptive facade, its design – mostly in case of critical or vulnerable environments – it must be preceded by an investigation on the dynamics that influence the vulnerability of the buildings, the analysis of the available natural resources (sun, wind, breezes, climate, etc.) and by simulations and tests on their use to evaluate the adequacy of the responses considering the energy efficiency aim. It can be achieved with a new concept in which the best facade is not the most insulated but the one allowing to correctly regulate the flow of transmitted heat, capture or release energy, control the flow rate of the ventilation and, finally, regulate its permeability according to the season, working conditions and user preferences. Nowadays, the mar-



Tab. 2 | Conceptual overview of a classification scheme for adaptive facades (Aelenei et alii, 2019).

ket and the research offer different types of facades characterized by an extraordinary level of innovation (Bendon et alii, 2019) mostly on the functionality and active responses of materials and components.

Besides the different definitions (Romano et alii, 2018) and specificities (Loonen et alii, 2015), every type of facade goes through three stages: (i) detect the environment (ii) process the acquired information and (iii) take physical action (movement or change in material property) to optimize internal environmental qualities in response to adverse external conditions. The level of adaptability (gradual or immediate) can be uniquely linked to the reaction time (seconds, minutes, hours, day-night cycle, season, year, ten-year span) and to the spatial scale (nano, micro and macro) according to when and where the change occurs. Daniel Aelenei et alii (2019; Tab. 2) have presented a classification scheme that combines the strengths of the different typologies through seven objectives/purposes that, on the one hand, help to understand the peculiarities (and philosophies) of the different adaptive facade systems, and on the other, define the tasks that an adaptive facade can perform, usually by balancing overall energy consumption, CO_2 emissions and life-cycle costs. In general, the adaptive components are controlled and managed in two ways (Loonen et alii, 2013): an 'intrinsic control', self-regulated and triggered by environmental stimuli that allow low-cost operations and maintenance (typical of passive systems); an 'extrinsic control' which can start after finding information (through sensors) and data processing with actions to be taken (through actuators).

Although the need for greater energy efficiency has regulated in recent decades a series of mandatory requirements aimed at implementing nearly Zero Energy Building (nZEB) or Zero Energy Building (ZEB), the facades of buildings must now meet new and more stringent requirements. Traditional materials with 'static' characteristics are no longer adequate to meet them, because they have optimal performance for specific needs, since they are optimized to ensure only one of the well-being conditions of cooling, heating or daytime lighting (Kasinalis, Loonen and Costola, 2014). Instead, facades should be more resilient and heating, cooling, lighting and energy production should be requirements handled by the envelope, planned since the design stage with new functions and peculiarities, with unprecedented performance and being an 'osmotic', 'selective', 'dynamic' and 'multifunctional' membrane (Goia, Haase and Perino, 2013), in other words 'adaptive', able to control and manage the variables of 'macro' phenomena through 'micro' and 'nano' responses, new scales of interest in the project.

Adaptive responses from 'micro' and 'nano': the PCMs | Among the different materials developed with the research at 'micro' and 'nano' scale, the Phase Change Materials (PCMs) can be a possible solution to reduce the energy demand in the building sector by reducing heating and cooling demand of buildings (Parameshwaran, Harikrishnan and Kalaiselvam, 2010). The Thermal Energy Storage (TES) systems allow to 'store' a certain amount of energy in the accumulation stage to be used at a later time

Thermo-physical Requirements	Kinetic Requirements	Chemical Requirements	Economical & Environmental Requirements
Appropriate melting temperature in the required operating temperature range	High nucleation rate in order to avoid super cooling of the liquid phase	Long term chemical stability of the PCM	Low price and effective availability
High latent heat of fusion	High rate of crystallization to satisfy demands of heat recovery from the storage system	No degradation after freeze/melt cycles	Non-polluting
High specific heat		Complete reversible freeze/melt cycle	Low environmental impact
High thermal conductivity of solid and liquid phases		No corrosiveness	Good recyclability
High density		Non-flammable, non-toxic, non-explosive materials for safety	Low embodied energy
Congruent melting of the PCM			Facility of separation from other materials
Cycling stability			
Small vapor pressure			
Small volume changes			
Little or no sub-cooling during freezing			
No segregation			

Tab. 3 | Thermo-physical, kinetic, chemical, economic and environmental requirements of PCM (source: Konstantinidou, 2010).

(Arce et alii, 2011), and among the different methods used for the heat energy storage, the Latent Heat Thermal Energy Storage (LHTES) uses the characteristics of phase change materials. The PCMs are materials capable of changing their status from solid to liquid and vice versa, depending on the amount of heat they absorb which becomes 'latent heat' during warm weather and 'released heat' during cold weather (Soares et alii, 2013). These materials are in a solid state at room temperature, but when it rises, they become liquid and accumulate energy in a latent form. The cycle is inverted when the temperature decreases again, they return to the initial temperature. In this case, the PCMs return to a solid state and in this phase change they release the previously stored energy as heat in the environment. Their thermal storage ability is higher than the one of a traditional material having with a certain mass. Thermoregulating materials represent an innovative technological solution in building design, as they give the possibility to reduce the daily fluctuations of the room temperatures through the reduction of indoor temperature peaks, and therefore of the energy consumption necessary for air conditioning the rooms. Furthermore, as a not negligible advantage, it must be noted that they are functional and operational without any type of external power source, and give dynamism and adaptation flexibility to external weather conditions.

One of the first PCMs used in passive solar systems is water. The Water Drum Wall – tested for the first time at the end of the 1940s by Hoyt Hottel and Massachusetts Institute of Technology of Boston's students – works in a rather simple way: the rays of the sun crossing the glass surface are intercepted by a mass of water or another liquid

	Organic	Parafin Non Parafin
Phase Change Materiales	Inorganic	Salt hydrate Metallic
	Eutectic	Organic-Organic Inorganic-Inorganic Inorganic-Organic

Tab. 4 | PCM classification (source: Memon, 2014).

Organic (paraffins and non-paraffins)	Inorganic Salt hydrates	Eutectics
They are available in a range of temperature	They possess high volumetric latent heat storage capacity	They exhibit application-specific sharp phase change temperature (melting temperature)
Values of latent heat of enthalpy are high (e.g., acids have much higher heat of fusion than the paraffins)	They possess low vapor pressure in the melt state	Exhibit slightly high volumetric thermal storage density than the organic compounds
Supercooling degree or superfusion effect is normally low during freezing process	They are non-corrosive, non-reactive, non-flammable, and not dangerous	They possess low or no segregation. Thermal reliability is good with congruent phase transition characteristics
Relatively low segregation even after several thermal cycles (thermal reliability). High thermal stability, congruent phase transition process	Have good compatibility with the conventional construction materials. Recyclable, cost-effective, and ease of availability	
Show self-nucleation and growth rate properties	Exhibit high latent heat of enthalpy and sharper phase transformation. High thermal conductivity with lower volumetric changes during phase change. Safe to the environment in terms of handling and disposing when compared to the paraffins	

Tab. 5 | Merits of the LTES materials (source: Parameshwaran and Kalaiselvam, 2016).

Organic (paraffins and non-paraffins)	Inorganic Salt hydrates	Eutectics
Density, thermal conductivity, and latent heat of fusion are inherently lower	Relatively high supercooling properties	Analysis of eutectics for thermal energy storage applications is limited due to the insufficient and non-availability of the thermophysical property data
Inflammable, less compatible with plastic containments	Low degree of nucleation (requires nucleating additives and thickening constituent materials)	In some cases, fatty acid eutectics evolve pungent odor, making them less suitable for PCM wallboard thermal energy storage applications in indoor environments
Larger volumetric changes are possible during charging and discharging (applicable to some grade of organic compounds); expensive by nature	Incongruent phase change and dehydration occur during freezing and melting cycles	
	Decomposition associated with phase separation. Compatibility with some building materials is limited. Exhibit corrosion properties when subjected to most metals. Slightly toxic in nature	

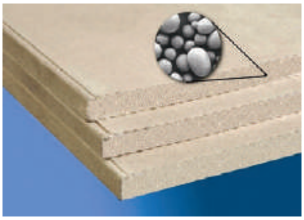
Tab. 6 | Limitations of LTES materials (source: Parameshwaran and Kalaiselvam 2016).

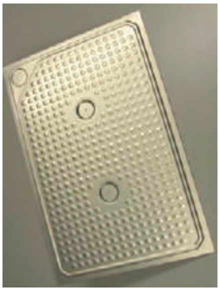
that converts them into heat, distributed by convection or radiation from a ventilated cavity to the served room, through the wall's internal face. The relation between the heat exchange surface and the indoor environment and the accumulation mass also determines the extent of the thermal transfer and its delay. Convective heat transfer through the liquid mass is faster than by conduction within a wall. Therefore, unlike what happens in the Trombe Wall, the heat transfer to the indoor environment by radiation and convection from the inner face of the wall is almost instant (Simmons, 2011).

In order to control convective motions, controls delaying heat transfer are necessary: on the inside of the water wall it is necessary to provide an insulating screen with openings at its top and base, while on the opposite side a mobile insulating screen that prevents overheating or, if necessary, outward heat loss (Emmitt, 2012). Starting from Hoyt Hottel pioneering initiative, through the years, other scholars have made an important contribution to the research and experimentation of Water Drum Wall (Briga-Sáa et alii, 2014; Zhongting et alii, 2017), entailing the thought that in the near future we might use water as real building material. «Build with water will represent a new frontier for sustainable architecture, provided that it is based on a new energy model, able to enhance the thermal mass and energy medium of the natural green fluid characteristics. The new architecture must be conceived as a living organism independent from the energy distribution networks, as a trans-structure, energetically self-sufficient, made of multitasking materials, capable of real-time responses for preserving the indoor comfort» (Sposito, 2017, p. 124).

Many studies have been, and still are, carried out on the use of PCMs in buildings to store heat energy, demonstrating the considerable interest for these materials allover the world (Kalnæs and Jelle, 2015; Cabeza et alii, 2011; Baetens, Jelle and Gustavsen, 2010). However, to use the PCMs we should verify a series of thermo-physical, kinetic and chemical requirements, those that have the greatest impact on their effectiveness, among others, are: High latent heat of fusion, High specific heat, High thermal conductivity of solid and liquid phase and liquid phases, little or no sub-cooling during freezing, non-toxic, low price and effective availability (Navarro et alii, 2018; Konstantinidou, 2010; Tab. 3). The various types of PCMs known to us do not have all the caracteristics listed in Table 3. The PCMs are categorized in organic, inorganic and eutectic: paraffin and non-paraffin are: organic PCMs; salt hydrates and metallics are inorganic PCMs; eutectic PCMs are divided into organic-organic, inorganic-inorganic and inorganic-organic (Tab. 4).

The PCMs – whether organic, inorganic or eutectic – have some lacks of performances, as stated in Tables 5 and 6 (Parameshwaran and Kalaiselvam, 2016). As it can be deduced from the Tables 5 and 6, the organic PCMs are available in a wide range of temperatures, are chemically stable, non-corrosive and nontoxic, do not undergo supercooling or segregation and have a high latent heat of fusion; at the same time they have a low thermal conductivity that could be improved by using a thin encapsulation. Inorganic materials have a good thermal conductivity and a high latent heat of fusion, and are not expensive and non-flammable, but for example salt hydrates have some limita-





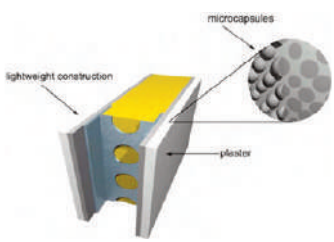


Fig. 5 | BASF's Micronal phase-change microcapsules enhanced gypsum board (credit: materialdistrict.com/material/micronal-pcm/).

Fig. 6 | GAIA PCM Energy Storage Ball: encapsulation of Phase Change Materials in a spherical shape with a diameter of 63, 80, 100 or 125 mm (credit: www.global-e-systems.com).

Fig. 7 | Macroencapsulation CSM (Compact Storage Modules): PCM in aluminum case (credit: www.rubitherm.eu/en/index.php/productcategory/makroverkaspelung-csm).

Fig. 8 | Schematic view of lightweight wall with PCM microcapsules integrated into the interior plaster (source: Schossig et alii, 2005).

tions such as supercooling, segregation and corrosion. On the other hand, metal PCMs do not have a suitable temperature range to be used in the building sector.

Among the most significant criteria for the selection of PCMs there is the melting temperature, whose value has to be compared with the climate zone where the materials will be used in the buildings. Several studies agree that high melting temperatures of PCMs seem more effective for warmer climates, while low melting temperatures can be more efficient for colder climates. Specifically, for the Mediterranean climate the best melting temperature range in winter goes from 18 °C to 22 °C, while in summer it goes from 25 °C to 30 °C (Xiao, Wang and Zhang, 2009; Cabeza et alii, 2011). Paraffin is the most used PCM for indoor cooling, even if in some cases salt hydrates and fatty acid were used. In the future, it would be advantageous to use within the same material and/or components, PCMs with different melting temperatures, to improve the energy performance both in warm and cold seasons (Souayfane, Fardoun and Biwole, 2016).

Given the above-mentioned limits, many studies to ameliorate the mechanism of latent heat energy storage of PCMs have been carried out. They focus on the integration methods of PMCs in building materials such as plaster, plasterboard, cement, insulation and glass (Ascione et alii, 2014; Goia, Perino and Serra, 2013) and the use of nanotechnologies (Jamekhorshid et alii, 2014; Parameshwaran and Kalaiselvam, 2016). PCM incorporation methods are mainly divided into two categories: direct and indirect methods. The direct methods of incorporation, both the wet mixing and immersion (Soares et alii, 2013), were mainly used in the past and have been abandoned due to the possible loss of PCMs and the direct interaction between PCMs and building material which can cause the deterioration of the mechanical and physical characteristics of the materials

(Cabeza et alii, 2007). To avoid loss and incompatibility problems caused by the direct contact between building materials and PCMs, most of the studies carried out in recent years have focused on indirect methods, that involve PCMs encapsulation. The encapsulation methods are mainly of three types, based on the size of the capsules: macro-encapsulation, micro-encapsulation and nano-encapsulation (Figg. 5-8). These sizes influence the stability of the PCM, since the smaller the capsule size is, the more durable a product is (Liu et alii, 2015).

The macro-encapsulation method consists of integrating the PCM in containers such as tubes, bags, spheres, porous materials or panels which are generally bigger than 1 cm (Cabeza et alii, 2011). Some of the containers developed as PCMs capsules are steel spheres (Cui et alii, 2017) or porous structures of light-weight aggregates – LWA (Cui, Memon and Liu, 2015; Niall et alii, 2017; Ma and Bai, 2018) to them is usually applied a highly conductive protective coating material to avoid leaks and at the same time increase the speed of heat transfer. Microencapsulated PCM refers to PCM particles enclosed in a thin solid shell (microcapsule) which is usually made of natural and synthetic polymers ranging from 1 μm to 1,000 μm (Navarro et alii, 2016) which prevents the leakage of the phase change material during the solid to liquid phase. Besides preventing PCM leakages during phase change, microencapsulation provides a quick heat transfer through its great surface area per unit of volume (Memon, 2014; Zubair, Hafiz and Shahab, 2018), improving chemical stability and thermic reliability, since the phase separation within the material, during the phase transition, is limited to microscopic distances (Navarro et alii, 2016).

Microencapsulated PCM can also be integrated in concrete. Most of the studies that have integrated microencapsulated PCM in concrete have used the replacement method – replace a specific quantity of fine aggregates with PCMs in the concrete mixtures (Jayalath et alii, 2016; Cao et alii, 2017), since they have a lower loss in resistance compared to mixtures in which PCM is used as an additive (Meshgin, Xi, 2012). Integrate PCM in concrete (Bentz and Turpin, 2007; Jayalath et alii, 2016; D'Alessandro et alii, 2018; Berardi and Gallardo, 2019), especially organic paraffin (Rao, Parameshwaran and Ram, 2018), can increase its heat storage ability, although PCMs can have some negative impacts on physical and mechanical properties of concrete, which depend from the PCM integration method used during the creation of the composite PCM-concrete (Cao et alii, 2017).

Researchers currently tend to reduce the size of the encapsulation to the nanoscale, to maximize the effects of its size and the surface area involved in the heat transfer (Khadiran et alii, 2016). Nanotechnology is the understanding and control of matter at dimensions between approximately 1 and 100 nanometres (a nanometre is equal to one billionth of a metre), where unique phenomena enable novel applications (National Nanotechnology Initiative Strategic Plan, 2011). On this level, fundamental properties such as force, surface/mass relation, conductibility and elasticity can be improved to create materials that can provide a better performance than present materials. In the architectural field, the advent of nanostructured materials concerns the entire building, from the basic structure to the wall-coatings, from lighting to energy production, and most important of all, it is considered crucial for energy efficiency in buildings.

The nano-enhancement of PCMs can be achieved with their encapsulation inside a nano-shell (Sari, Alkan and Bilgin, 2014) or a nano fibre (Moghaddam, Mortazavi and Khaymian, 2015): there are several experimentations that have used PCM nano capsules to improve the thermal properties of cellulose nano fibres (Alzoubi, Albiss and Abu sini, 2020) or PCM nano-encapsulated in a silica shell (De Matteis et alii, 2019), highlighting how the use of nanomaterials can help overcome some limits of PCMs, such as low thermal conductivity (Fang et alii, 2013; Ma, Lin and Sohel, 2016). Other researches concerned the improvement of paraffin thermal conductivity through the dispersion of titanium dioxide nanoparticles (Sami and Nasrin, 2017) but also the development of new phase change materials enhanced with carbon nanotubes (C-PCM) and with a polymer-organic hybrid shell which reduce internal temperature variations and absorb more heat (Cheng et alii, 2020).

Final considerations and future developments | In the near future, the building industry will have to make a meaningful contribution to the protection of ecosystems vulnerable to collapse and the reconstruction of those that have already been affected, also through a significant reduction in the energy required for building operations. ‘Passive’ systems can play, in this sense, a strategic role, especially if the research will give value to bioengineering and naturalistic engineering methods and techniques tending towards practices designed «[…] to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits» (Cohen-Shacham et alii, 2016, p. 5). This change of perspective will lead the way for a new paradigm that will overturn current approaches: the aim of the projects will no longer be to control natural phenomena to subject them to contingent short-term needs but to support the (unpredictable) dynamics of natural systems, ensuring the operating conditions of systems, subsystems, components and building materials in the long term.

In this sense, Ernesto Antonini (2019) observes that the new paradigm given by biomimetic adaptive envelopes will generate two relevant consequences. The first will be to replace the ‘economic benefits’ objective for those who fund and build a single building with a long-term vision that will concern ‘collective benefits’ mostly for future generations, strengthening the idea that if the planet is a ‘common good’ it needs a development model capable of fixing the catastrophic effects caused by the indiscriminate use of non-renewable resources and the emission of CO_2 into the atmosphere (Tirole, 2017). The second will concern the methods of analysis of natural phenomena: action strategies and intervention planning will have to be systemic and multiscalar, employing shared operational and metric techniques to assess credible cost/benefit balances with the tools provided by Environmental Product Declarations (EPD) methods, of the Life Cycle Assessment (LCA) and their extension to investigate the social aspects (s-LCA) that come into play (Sala et alii, 2015). A vision that analyses the physical area at different scales (resources, materials, buildings, cities, ecosystems and planet) and the social sphere (psychophysical well-being, work, production, consumption, mobility, etc.) and that is aware of the interconnectedness between global and local level is the unprecedented element of this innovative approach that can be implemented immediately thanks to pioneering good practices, as the RELi – REsilience action List by Perkins+Will (Eskew+Dumez+Ripple, 2014) or the REDi – Resilience-based Earthquake Design Initiative for the Next Generation of Buildings by ARUP (2013). Even if they use different methods and standards for assessing resilience, can both be integrated with the most common Sustainable Building Rating Systems.

The great number of published scientific papers and experimental research carried out in the last decade show that the change is occurring and that the future trends in technologies for adaptive facades can be divided into four main categories (Attia, Lioure and Declaude, 2020): 1) Human-centred Design – New ways of working, living and learning, increased knowledge on the well-being and health of users and a higher productivity boost the demand for comfortable and instantly customizable environments (Attia, Garat and Cools, 2019, Luna Navarro et alii, 2020); 2) Smart Building Operating Systems (SBOS) – an increasing number of components and building elements are managed through the BOS: a software platform for smart facades that implements the use of the IoT and digital applications in buildings by providing services and connectivity to SMACIT technologies – social, mobile, analytics, cloud, smart grid and IoT – to boost user interaction (Dery, Sebastian and van der Meulen, 2017); 3) Service-driven solutions – the risks and uncertainties linked with the functioning of adaptive facades are pushing the users to outsource performance optimization, monitoring and maintenance services directly to suppliers and manufacturers, because they know the design and engineering of facades in depth (Azcarate-Aguerre, Den Heijer and Klein, 2017); 4) Circularity and materials – European Union law making on circular economy, fosters the industry to produce efficient adaptive facades but using materials providing an environmental gain during their life cycle and that are recyclable within closed and 'regenerative' economic cycles (Ellen MacArthur Foundation, 2013).

Currently the nZEB and ZEB represent less than 5% of new buildings. This percentage is higher in some Countries, such as France, that has very restrictive energy regulations. In the 'rapid transition' scenario for a sustainable future promoted by the International Energy Agency high-performance and near-zero-energy buildings will be more than half of new buildings in 2030, more in advanced economies. If, in the next decade, every country implements specific energy standards for each geographical area, nation, region and climatic zone, especially by enhancing passive adaptive systems and innovative materials for insulation to limit heat loss in cold climates and reduce solar gain in hot climates. To this purpose, it is essential to organize a strategic plan to lead the building industry in a (quick and aimed) transition stage towards clean energy, low energy consumption and reduced CO_2 emissions and based on three key pillars (IEA, 2019c): Sufficiency – reducing the energy demand and limit expensive unnecessary technological/plant investments through adequate and careful planning and design of buildings without reducing (on the contrary, improving) the well-being standards for users; Efficiency – improve the energy performance of building materials, components and technologies through market policies and actions encouraging the transition to efficient and innovative solutions; Decarbonisation – development, promotion and immediate marketing of already tested technologies that allow to enhance renewable energy sources. The implementation (that is reaching the goals) of this strategic plan is technically possible if the best performing products already available on the market are used since the beginning, through specific 'mandatory performance targets' and 'incentives' useful to cut the high costs of these new materials.

The research on PCMs – which can play an important role in controlling energy consumption for heating and cooling in indoor environments – certainly refers to these three pillars. Taking into account the experimentation and afore-mentioned research, PCMs can take the role of new 'thermoregulatory' paradigm for architecture. To do so, it will be necessary to invest more in research, reasonably assuming that the return on the investment will not only be economic (management costs are significantly lower than mechanized adaptive systems) but also social and environmental and examine in depth a number of issues on various subjects. About environmental issues, it will be necessary to define a new 'adaptive' energy model, based on the physical and thermo-hygrometric characteristics of PCMs, tending, due to their high capacity to absorb latent heat, on the one hand, to the almost energy self-sufficiency in relation to the heating and cooling needs of a building, on the other, to the transfer of surplus heat energy to neighbouring more energy-intensive public buildings, through a system of heat storage and networks.

Conversely, regarding the technological issues, some research areas can concern the creation and development of new PCMs for specific geographic and climatic contexts and building elements and components in which integrate them. It would be important to focus on materials having PCMs with different melting temperatures, to improve the performance of buildings both in warm and cold seasons (Souayfane, Fardoun and Biwole, 2016). Regarding the environmental issue, it should not be overlooked that these innovative storage materials/systems should be analysed especially by taking into account their whole life cycle. Currently, there are only few LCA studies and researches available, limited to paraffin which has significant Global Warming Potential and Totala Use of non-Renewable Primary Energy Roseurces impacts, and to salt hydrates that have a minor impact (Kylili and Fokaides, 2016; Horn et alii, 2018; Nienborg et alii, 2018; Di Bari et alii, 2020).

For the elements and components integrating the PCMs it will be necessary to research on 'multifunctionality' requirements, minimizing the number of technical, durability and endurance elements, while evaluating the overall performance of the system according to an adaptive response to variable (and not always predictable) mechanical and thermal stresses. Moreover, since the new multifunctional components will characterize future architectures with their own shape, size and section, it will be necessary to deepen studies on manufacturing systems – for example digital manufacturing (Sposito and Scalisi, 2017) – allowing, according to the individual needs of designers, the personalization of the components and an adequate integration with PCMs, and also a linguistic and formal variety, suited to the intervention background.

In conclusion, to use PCMs as 'thermoregulatory' materials to be integrated into 'adaptive facades' there is definitely a long road ahead but, with thanks to the abovementioned experimentation and research, it seems set. On the one hand, it seems that, thanks to the use of nanotechnologies, the limit of these materials can be found in the visionary skills of researchers, and on the other, we still must understand how much and when these technologies and materials will be widespread enough to allow a significant reduction of the energy necessary for heating and cooling buildings.

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The ability of ‘change of scales’, work on more different scales – multiscalarity – create new ones or change the meaning of the scales commonly accepted, it is common practice in the approach to the project and has always concerned architects, engineers, designers and artists for the multiple symbolic and real meanings of the size of a territory, a city, an architecture and an object. However, it can provide a range of opportunities even in different contexts such as economy, politics, culture, etc. The concepts of scale and size are fundamental to link, in a systemic point of view, the detail with the big picture, the detail with the group, to interpret and represent, to discretize and recompose elements and parts that stand in a hierarchy or interconnection relation, to investigate the physical and social, to outline critical issues and potential, but especially to establish the importance of relational aspects between the group and its component as a way to understand their identity, their nature and organization, their regulation rules and the role played in different contexts, namely the fundamental elements to identify the form and structure of a territory, a city, an architecture and an object.

Therefore, the multiscalar approach can be considered as an important design working tool that, in a systemic point of view, can foster the proposal of adequate strategies for action and planning of sustainable actions, developing new methods, working techniques and shared measurements, through well-considered hierarchies of priorities necessary to optimize the choices of the project and to determine reliable cost/benefit balances (especially of environmental nature). In this regard, the book ‘From Mega to Nano: the complexity of a multiscalar project’ collects essays and critical thoughts, researches and experimentations on the subject providing some starting points for debate for the international scientific Community.

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