# APPLICATION OF SMART MATERIALS IN SUSTAINABLE ARCHITECTURE

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# APPLICATION OF SMART MATERIALS IN SUSTAINABLE ARCHITECTURE

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## ABSTRACT

APPLICATION OF SMART MATERIALS
IN SUSTAINABLE ARCHITECTURE

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Today's sustainable buildings depend on conventional products and materials, existing methods of analysis and design tools. The next generation of sustainable buildings will have to be radically different from those of today and will be designed using new approaches to materials that are expressed in this study. Smart materials are one of the components for these new approaches. These new materials, which are integrated with the environment, produce renewable energies, maintain themselves, minimize energy consumption and/or maximize the usage of natural light.

The contribution of smart materials in architecture gives architects the opportunity of designing smart buildings with lightweight structures and new building elements that react to environmental conditions. The increasing interaction with the environment also leads architects to the following question: Can these material properties be used for supporting the sustainability of the building? The Increase in interaction with the environment could ensure that buildings are more compatible with their surroundings. This compatibility could support ecologically sustainable environments and this is the main idea that this study deals with. In order to examine this idea, a theoretical research about sustainable architecture has been conducted. This research puts forth selection criteria for smart materials, which are examined from the viewpoint of an architect. These smart materials are selected out of a wide range of materials with an intense research according to their application possibilities in architecture.

The aim of this thesis is to analyze the application of smart materials in sustainable architecture. While the study covers a research on smart materials, it also contains a detailed examination of those selected smart materials according to their availability for use in sustainable architecture. In this context, this study examines the concept of sustainability and sustainable architecture. It proposes and questions the application of smart materials in sustainable architecture.

In this study, the sustainability of smart materials themselves is not analyzed rather the properties of these materials are studied to find out how they can support sustainability. Therefore, the criteria to choose materials are related not to the chemical or physical properties of the materials but to their application in the sustainability of a building.

**Keywords:** Smart Materials, Sustainability, Ecology, Architectural Materials, Technology

**ÖZET**

AKILLI MALZEMELERİN
SÜRDÜRÜLEBİLİR MİMARLIKTA KULLANIMI

Özgönül Şensan, Senem

Tasarım Yüksek Lisansı, Güzel Sanatlar ve Tasarım Fakültesi

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Günümüzün sürdürülebilir yapıları bilindik ürünler ve malzemelere, mevcut analiz ve tasarım yöntemlerine dayanmaktadır. Yeni nesil sürdürülebilir yapılar bugünkülerden önemli ölçüde radikal yönde farklı olacaktır ve bu çalışmada bahsedildiği gibi malzeme kullanımına getirilecek yeni yaklaşımlarla tasarlanacaktır. Akıllı malzemeler bu yeni yaklaşımların bir parçasıdır. Tepkisel davranışları bulundukları çevre ile şekillenen bu yeni malzemeler yenilenebilir enerjiler üretebilecek, kendilerini onarabilecek ve kendi bakımlarını sağlayabilecek, enerji tüketimini minimize edebilecek ve doğal ışığın maksimum kullanımını sağlayabilecek özelliklere sahiptir.

Akıllı malzemelerin mimarlıkta kullanımı, mimarlara hafif yapı sistemli akıllı binalar ve çevresel koşullara göre tepki veren yeni yapı elemanları tasarlama fırsatını vermektedir.

Çevre ile giderek artan etkileşim aynı zamanda mimarları şu soruya yönlendirmektedir: Bu yeni malzemelerin özellikleri yapılarda sürdürülebilirliğin desteklenmesi için de kullanılabilir mi? Çevre ile artan etkileşim yapıların aynı zamanda bulundukları ortamın koşulları ile uyumlu olmalarını da sağlayabilir. Bu uyumluluk ekolojik olarak sürdürülebilirliği destekleyebilir. Bu düşünce bu çalışmanın ana fikrini oluşturmaktadır. Bu fikri incelemek amacıyla bu çalışma kapsamında sürdürülebilir mimari ile ilgili bir araştırma yürütülmüş, bu araştırma bir mimarın bakış açısıyla birçok akıllı malzeme arasından konu ile bağlantılı olanların seçim kriterlerinin belirlenmesini sağlamıştır. Bu akıllı malzemeler birçok malzeme içinden mimaride uygulanabilirlik olasılığına göre seçilmişlerdir.

Bu tezin amacı akıllı malzemelerin sürdürülebilir mimarlıkta kullanımının incelenmesidir. Çalışma, akıllı malzemeler ile ilgili bir araştırmayı kapsarken aynı zamanda seçilen akıllı malzemelerin sürdürülebilir mimarlıkta kullanılma olasılığını da incelemektedir. Bu bağlamda, bu çalışma sürdürülebilirlik ve sürdürülebilir mimarlık kavramlarını incelemekte ve mimarlıkta kullanılabilecek akıllı malzemeleri belirlerken bu malzemelerin sürdürülebilirlik açısından yapılarda kullanımını sorgulamaktadır.

Bu çalışmada, akıllı malzemelerin kendilerinin sürdürülebilirliğini incelemek yerine sahip oldukları özelliklerin sürdürülebilirliğe nasıl destek olabileceği üzerinde durmaktadır. Bu nedenle, malzeme seçim kriterleri malzemelerin kimyasal veya fiziksel özelliklerinin sürdürülebilirliği ile bağlantılı değil, bu malzemelerin bir yapının sürdürülebilirliğine katkısı ile bağlantılı olarak belirlenmiştir.

**Anahtar Kelimeler:** Akıllı Malzemeler, Sürdürülebilirlik, Ekoloji, Yapı Malzemeleri, Teknoloji

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# 1. INTRODUCTION

Man's journey of invention has brought him from prehistoric times to our century, to the digital age. In the timeline of scientific inventions and discoveries, there are very important events like the Industrial Revolution between the late 18th and the early 19th centuries. The Industrial Revolution has marked a major turning point in human history through industry and the manufacture of machinery. Meanwhile, humans have improved their knowledge about nature, Earth and space and developed a vision about themselves and their environment in which they live. This knowledge that is gained throughout history and the ability to control the environment has also brought them an awareness of their responsibility towards humanity and other living forms and the shared natural environment. The responsibilities of conserving the eco-system, the awareness of man-made hazards to the environment and the loss of natural resources have formed global policies. From the beginning of the 1970s, the awareness of the need to protect nature and the consequent use of scientific power to repair environmental damages has improved. Since global warming, pollution and the increasing shortage of water and food are becoming undeniable facts, ecological studies have become important topics. In 1972, the United Nations has held the first international conference on environment in Stockholm. This conference is the origin of the phrase "Think globally, act locally" and is the first step of taking action globally. In 1997, a similar conference has followed this understanding and this global awareness has lead to the Kyoto Protocol[1]. These conferences have highlighted the increasing dangers of the green house effect and its consequences leading to global

[1] "The Kyoto Protocol, an international and legally binding agreement to reduce greenhouse gases emissions world wide, entered into force on 16 February 2005." Today it covers more than 170 countries globally and more than 60% of countries in terms of global greenhouse gas emissions (http://unfccc.int/essential_background/items/2877.php; cited 10.02.2008). Turkish government approved to join to the Kyoto Protocol in 2008.

changes in the climate. In Kyoto, most of the world's nations have recognized the importance of looking at ecology from a global point of view, and taking into account the impact of humans on Earth's environment.

There are reflections of these actions in every field, including architecture. The Building Research Establishment's Environmental Assessment Method (BREEAM), The Leadership in Energy and Environmental Design (LEED) and Green Building Rating System are most important regulations for buildings. These efforts can change these impacts on Earth and human beings. The regulations are the guidelines of ecological architecture that will shape the 21st century. The emergence of the importance of environmental issues since the 20th century has introduced the concept of 'sustainability' to architecture as a new quality. In *The Ten Book of Architecture,* Vitruvius writes that a building must exhibit three qualities, *firmitas, utilitas* and *venustas,* namely it must be strong or durable, useful, and beautiful (80). Sustainability brings new concepts to architecture, such as ecology, conservation of natural resources and minimization of energy consumption, and brings new approaches to architecture in addition to the qualities that Vitruvius describes. The necessity for an increase in the use of clean energy sources in sustainable buildings brings new qualities to architectural design. Developments in sustainability change in our life styles and affect the understanding of building construction.

"Architecture is the first manifestation of man creating his own universe, creating it in the image of nature, submitting to the laws, which govern our own nature, our universe" (Le Corbusier 40). Architecture gives shape to the environment through the application of materials. Materials play a very important role in the design process of a building and are an indispensable the component of architecture. The improvements in material science and contribution of other technologies like nanotechnology have changed expectations from materials. Researchers have developed such advanced materials that they respond to the surroundings and change their properties accordingly. These new materials that becoming part of architecture are called ‘smart materials’. New buildings responsive to the needs of the user and the conditions of the environment are being designed.

Materials influence every segment of our lives including transportation, housing, clothing, communication, recreation and food production. Historically, the development of societies and cultures has been tied to people’s ability to produce and manipulate materials to fulfill their needs. Throughout the history of architecture, the application of materials has played a very important role in the design and construction process of a building. Human kind has attempted to create spaces to meet their needs and while creating spaces they have used and formed materials around them.

Michelle Addington and Daniel Schodek state, “The relationship between architecture and materials had been fairly straightforward until the Industrial Revolution. Materials were chosen either pragmatically – for their utility and availability – or they were chosen formally – for their appearance and ornamental qualities” (2). Parallel to the developments in material science, techniques of construction and the manufacture of building materials have evolved. Mies van der Rohe emphasizes the relation between architecture and material with his statement that the architectural expression starts with understanding the meaning of the raw material (Schulze 20). Louis Kahn posed a question in the early 1970s that has since attained legendary status within architectural circles. "What does the brick want to be?" He replies; "It wants to be something greater than it is" (271). The relation between architecture and material is obvious; material is the main instrument for architects to form the built environment. Moreover, new materials propose new approaches to architecture in the 21$^{st}$ century. In this context, the integration of smart materials into architecture brings buildings one-step closer to sustainability since the responsiveness of these materials enables them to react to environmental changes.

This thesis aims to present an analysis of the application of smart materials in sustainable architecture. It starts with the composition of a theoretical basis to understand the concept of sustainability and sustainable architecture. Following this basis, selected smart materials are examined. This examination is made in four main groups; high insulation, self-maintaining, energy generating and shape changing smart materials. These groups are composed according to the areas that the materials can be used to support the sustainability of a building. This thesis conducts a technological survey that supports sustainability. To compose this technological survey, different approaches and technologies will be analyzed and incorporated.

This study emphasizes the need to use smart materials more consciously. It suggests to benefit from these materials more extensively in architecture and to invent new design solutions with the help of smart materials; particularly solutions that provide sustainability. The study examines the state of environmentally-sustainable architecture, determines the characteristics of smart materials, and analyzes these materials according to their ability to be applied in environmentally sustainable architecture in the future.

The thesis is composed of five chapters. The introduction focuses on the importance of the relationship between materials and architecture, particularly smart materials and sustainability. In the second chapter, the concept of sustainability and sustainable architecture will be analyzed. The third chapter contains a research on smart materials and a detailed examination of some of these materials selected according to their availability for use in sustainable architecture. Through sample projects, the fourth chapter will cover available application areas of smart materials according to their contribution to sustainable architecture. In the conclusion, the future of smart materials and their future application possibilities in sustainable architecture will be discussed.

## 2. SUSTAINABILITY AND ECOLOGY IN ARCHITECTURE

Throughout human history, the environment has been an evident concern. Various kinds of human activities have caused a high consumption of the limited natural resources and have resulted in a series of global environmental problems, including global warming, land degradation, over-population, fresh water scarcity, air pollution, toxin proliferation and species extinction (Kaplan 44-46). As a result, consciousness about the importance restoring and protecting the natural environment has increased.

This chapter examines the literature related to sustainability and sustainable architecture. To compose a theoretical basis for this thesis a brief historical background will be followed by the discussion of the relation between sustainability and ecology, and the contribution of technology in sustainable architecture. Issues of environmentally sustainable architecture are discussed, focusing on technological approaches and the scope of materials related to the subject.

Before focusing on the relationship between sustainability, ecology and architecture, it is significant to define sustainability and ecology thoroughly. The 1933 edition of the *Oxford English Dictionary* does not mention the word ‘sustainable’ or ‘sustainability’, which is derived from the Latin word ‘*sustinere’*. When term sustain is introduced in to English the word defined as "to hold up; to bear; to support; to provide for; to maintain; to sanction; to keep going; to keep up; to prolong; to support the life of” (Cohen 30). Generally speaking, the use of the adjective "sustainable" or the noun "sustainability" implies three possible meanings, sustainable development, sustainable growth, and sustainable use. "Sustainable growth is a contradiction in terms: nothing physical can grow indefinitely. Sustainable use is only applicable to renewable resources. Sustainable development is used in this strategy to mean improving the quality of human life whilst living within the carrying capacity of the ecosystems" These three meanings constitute the connotation of the terms "sustainable" and "sustainability" (IUCN, UNEP, and WWF 25)

The first known use of the term "sustainable" as in the meaning of the human use of natural resources appears as early as 1798. The concept is first mentioned in the writings of Thomas Malthus in 1798 and John Stuart Mill in 1848 and then later, in Germany, by Martin Faustmann in 1849, in his use of a similar concept to calculate the forest rotation period needed to maximize returns in German forests (Kohn 86).

The contemporary meaning of the concept is used in many different ways. The most common one is that is used by the United Nations' Stockholm Conference on the Human Environment in 1972. This conference has marked the first great international meeting on how human activities harm the environment and put humans at risk. In 1987, the United Nations' World Commission on Environment and Development has defined "sustainable development" or sustainability as, "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland 43). The definition is based on two concepts, the concept of present and future needs comprising of the conditions for maintaining an acceptable life standard for all people and the concept of the limits of the capacity of the environment to fulfill these needs, determined by the state of technology and social organization (Boehland 80). Other definitions of sustainability are related with social and economical issues (Cole 55).

The factors that have pioneered the Stockholm Conference start with the Industrial Revolution. Between 1760 and 1860, the Industrial Revolution has resulted in a large-scale means of production and the use of massive quantities of raw materials. As consequence, between 1880 and 1930, conservation movements have developed and lead to the awareness of the negative impacts of the Industrial Revolution on the natural environment. This movement has received increasing attention after the environmental movements formed in the 1960s. During the 1960s, there was an environmental degradation, which conducts “awareness on many fronts that industry was creating, an imbalance between economic and natural forces without any concern for pollution or renewability” (Larson 34). As a consequence of the environmental movements formed in the 1960s, the Stockholm Conference has lead to a global movement for the concept of sustainability. After the Stockholm Conference, United Nations has organized another conference on the environment and development in Rio de Janeiro in 1992 (Edward 22). As a result of these movements, environmental concerns have been accepted as a fundamental issue, and have become more and more rooted in people's consciousness. “More remarkably, the human societies increasingly started recognizing the inadequacy of the "technocratic" paradigm with respect to long-term sustainability” (Todd and Todd 10).

The concept of sustainability is related the equilibrium within our planet continued growth and human development. For natural ecosystems, sustainability can be defined as the carrying capacity, that is, “the amount of use that can be sustained over time without degradation of the system” (Childs 40). There are many other definitions of the term sustainability. They differ from place to place and from time to time, and depend on the values and resources. Basically, sustainability is the capacity of preserving a certain process or state. It “implies a moral and ethical responsibility towards the basic values of life, with far reaching benefits that concern the environment, society and economy” (Childs 40).

The definition of sustainability proposed at the Stockholm Conference does not specify the ethical role of humans to ensure their continuing existence on the planet. It also fails to embrace the value of all other constituents participating in the global ecosystem. In response to the human-centered definition of sustainability, in 1972 ecologist Arne Naess offers a further critique: "Development is not sustainable, if it is not ecologically sustainable" (Lafferty 13).

The term ecology is the combination of two Greek words; ‘oikia’ which means house and ‘logos’ which means logic, science and also universal code (Crowther 115). According to its etymology, ecology can be defined as a structure that is in harmony with Earth. In other words it covers the environment of all the living or non-living organisms on Earth. The habitat that these living and non-living organisms form, is called an ecosystem. Ecology also means “the scientific study of the distribution and abundance of life and the interactions between organisms and their natural environment” (Crowther 115). The roots of ecology go back to the ancient civilizations, however; the term is coined by German biologist Ernst Haeckel in 1866. He defines ecology as “the comprehensive science of the relationship of the organism to the environment” (Crowther 115). An ecosystem sustains itself for millions of years so, in this context, sustainability is solidly linked to ecology and its concept can be seen as a simulation of the ecosystem. In *The Closing Circle: Nature,* *Man and Technology* published in 1971 biologist Barry Commoner has formed the four laws of ecology. According to Commoner, “The first law of ecology is that everything is related to everything.” The second law is, “[e]verything must go somewhere. There is no "waste" in nature and there is no “away” to which things can be thrown.” Commoner states the third law as, “Nature knows best. Humankind has fashioned technology to improve upon nature, but such change in a natural system is likely to be detrimental to that system.” Finally the forth law states “[t]here is no such thing as a free lunch. Everything comes from something. There is no such thing as spontaneous existence” (Williams 1).

Ecology is the study of the relationship of plants and animals with their environment. In this context, the understanding of ecology and sustainability overlap. Daniel Williams’ statement strengthens this argument: “[I]t is the study of that spatial connectivity between organism and environment that makes ecology an excellent model for sustainable design” and he states that ecology is a model for sustainable design “by showing pathways between energy and material flows” (Williams 2). That is to say, this model illustrates the flows of energy and materials, the distribution of which is powered by sustainable energies, including the sun, gravity, and natural cycles thus architects can follow this model to design sustainable buildings. As Commoner states, the third law of ecology, “[n]ature knows best.” Ecology will provide a framework that will produce sustainable results. Because of this strong link to ecology, the term ‘environmentally sustainable architecture’ is used interchangeably with ‘green architecture’ and ‘ecological architecture’.

## 2.1. Theory of Sustainability In Architecture

Humans construct the built environment to shelter themselves and their possessions and to meet a variety of needs critical to human survival and prosperity. The built environment has a significant influence on the natural environment. Transforming resources into building materials and putting them together to use in residential and commercial construction projects result in tens of millions of tons of greenhouse gases, air and water pollution, and other wastes. Global climatic change is a major issue for the future, and architecture has an important impact on that in 2003, *Metropolis Magazine* has published a study that states, "[a]rchitecture consumes 48% of all energy in the United States and is responsible for more $CO^2$ emissions than transportation or industry" (Shaviv 463). The numbers indicate the impacts of U.S. buildings on resources, which are announced by Environmental Information Administrations' in 2008 Report of Annual Energy Outlook, strengthen this situation. It states that 40% of the primary energy, 72% of the electrical energy is used by buildings. Buildings are also responsible for 39% of $CO^2$ emissions (Environmental Information Administration 31). The numbers indicated by Energy Information Administration in 2006 also causes architecture to be in first place in Global $CO^2$ emissions. In addition to these impacts, usage of materials and production of wastes is the other areas that architecture contributes the contamination of the environment. As Worldwatch Institute states in their paper "A Building Revolution: How Ecology and Health Concerns are Transforming Construction" in 1995 buildings use 40% of raw materials globally and United States Environmental Protection Agency estimates that "136 million tons of building-related construction and demolition debris was generated in the United States in a single year" (United States Environmental

Protection Agency 45). These researches bring out the reality that Buildings are one of the heaviest consumers of natural resources and account for a significant portion of the greenhouse gas emissions that affect climate change.

Although sustainability may appear to be a contemporary concept, architectural historian James Steele writes in *Ecological Architecture* that designing with ecological consideration has been a part of architectural developments throughout history. He suggests that although architects such as Charles Rennie Mackintosh, Le Corbusier, and Kahn not usually associated with sustainability; they all present aspects of sustainable design. He adds contemporary “high-tech” architects such as Richard Rogers and Renzo Piano to his argument. "Architecture presents a unique challenge in the field of sustainability. Construction projects typically consume large amounts of materials, produce tons of waste, and often involve weighing the preservation of buildings that have historical significance against the desire for the development of newer, more modern designs" (Mendler 8). The challenge is to design and build intelligently so that buildings can be environmentally sustainable[2]. After the Stockholm Conference, sustainable design has emerged as a guiding paradigm to create a new kind of built environment. The first generation of sustainable design is based on small-scale experiments (Van der Ryn and Cowan 32). Starting with the 1992 United Nations conference in Rio de Janeiro, scientists have indicted that sustainable development is the only allowable form of cohabitation between humanity and the environment. Therefore, sustainability has become a research topic for many disciplines, including architecture. Recently, new design methods, materials and construction techniques have been developed to improve the sustainability of

[2] This study examines only the environmental dimension of sustainable architecture, excluding economical and social sustainability.

buildings. Based on the original meaning of sustainability, sustainable architecture refers to a certain kind of architecture that interacts with the environment harmoniously rather than in confrontation manner. Ultimately, sustainable architecture aims at restoring the relationship between buildings and their environment.

Designers, architects and builders are becoming increasingly interested and involved in sustainable design as they realize its benefits. This interest is strengthened through many building environmental assessment methods that have been developed to evaluate the environmental performance of buildings, and to promote sustainable building practices. Some of the sustainable buildings rating systems or assessment standards, which have been developed over the past few years, are listed below.

- BREEAM - Building Research Establishment Environmental Assessment Method
- LEED - Leadership in Energy and Environmental Design
- Minnesota Sustainable Design Guide
- The Green Building Challenge assessment framework

BREEAM and LEED are the most commonly known and intricate systems. BREEAM, Building Research Establishment Environmental Assessment Method is the first method, originally designed by the Building Research Establishment in the United Kingdom in 1988 and has been launched in 1990 (Bryan 1). On the other hand, LEED, Leadership in Energy and Environmental Design has been developed by the United States Green Building Council (USGBC) in 1994 and started to be implemented in 1998 (Mendler, Odell and Lazarus 7- 8).

These certification systems cover a wide range of environmental issues rather than one single issue or performance criterion such as energy efficiency (Cole 2). Most of these methods deal with site selection criteria, the efficient use of energy and water resources during building operations, waste management during construction, demolition and operation, indoor environmental quality, transportation services, the selection of environmentally-preferable materials, design strategies, and building management practices (Wayne 1). Although, their approach to dealing with various issues is different, they have a number of components in common.

Each assessment method rates the performance of the building by using a certain scale of measurement. Points are related to the various performance criteria, which are calculated to obtain an overall performance score. These rating systems are regarded by many as effective means for elevating the performance level beyond the current established standards. Designating buildings as having high performance standard would encourage building professionals, investors and tenants to seek higher building performance levels and consequently changes market demand (Larson 1). With the use of these assessment methods architects are conducted to produce suitable solutions and design sustainable buildings.

### 2.2. Different Approaches to Sustainable Architecture

Sustainable architectural theories comprise a wide range of opinions and points of view. The most significant approaches are low-technological, high- technological and biomemetic sustainability in architecture. Perhaps one of the most difficult challenges in sustainable architecture is the disagreement between the low technological and the high-technological approaches. Both arguments have clear values “but dismissing one in favor of the other may be detrimental to the advancement of sustainable design” (Steele 92).

The technological approach to sustainable architecture contains two different approaches; low-technological and high-technological approaches. Low-technological architecture includes buildings made of adobe, rammed earth, bales of straw, wood, bamboo and recycled materials such as tires and paper however; it is not limited with local materials and local environmental conditions. The term low-tech means the crafts and tools that can be practiced or fabricated with a minimum of capital investment and with little or no use of machinery or tools with complex mechanisms; “those can be stamped with the designation hand wrought or hand-made” (Mostaedi, Broto and Minguet 36). In *Sustainable Architecture and Urbanism: Concepts, Technologies*, Examples Dominique Gauzin-Müller, Nicolas Favet and Kate Purver also mention conflicting technological approaches to sustainable architecture and they state that the first steps of low-tech approach start in the early 1970s, following the first oil shock with the proposition of environmental alternatives in mostly housing and small-scale cultural and educational buildings. “In the wake of the anti-authontarian movements of May 1968, some architects rejected what they saw as the stiffness and coldness of modernism and began to encourage the involvement of end-users in the design, and sometimes the construction of more "friendly" buildings” (16). Some of the outstanding projects are the student apartments at Woluwé Saint Lambert designed by Lucien Kroll in 1970, the Vandkunsten Studio's Tinn-garden housing project near Copenhagen in 1978 and

Arcosanti project in Arizona designed by Paolo Soleri in 1970. “Paolo Soleri is putting into practice his own concepts of "arcology" or architecture consistent with ecology” (Gauzin-Müller, Favet and Purver 16). Although different natural materials are used in low-tech architecture timber is commonly used in most of the projects because it is naturally warm, light and easy to work with.

(http://homeusers.brutele.be/kroll/auai-project-ZS.htm; cited 27.02.2009)

**Figure 1** Student apartments designed by Lucien Kroll (1970)

(http://www.e-architect.co.uk/architects/tegnestuen_vandkunsten.htm; cited 27.02.2009)

**Figure 2** Vandkunsten studio's Tinn-garden housing project (1978)

(http://seattletimes.nwsource.com/ABPub/zoom/html/2004419777.html; cited 27.02.2009)

**Figure 3** Arcosanti project designed by Paolo Soleri (1970)

High technology, on the other hand, follows contemporary techniques. It generally relies on the idea that all problematic environmental issues such as resource shortages can be solved simply by developing new technologies. These technological solutions do not only provide effective renewable energy sources; “coatings, control systems and computer systems that respond to optimize energy use based on weather and interior conditions, energy recovery systems that incorporate desiccants to shift both heat and humidity, and materials incorporating post-industrial and post-consumer waste are typical examples of a high technology approach” (Kibert 336). High-tech architecture is symbolized by the towering office buildings made of steel and glass structures. Pioneer architects including Norman Foster, Renzo Piano, Richard Rogers, Thomas Herzog, Françoise-Helene Jounda and Gilles Perraudin, come together to form the Read group - Renewable Energies in Architecture and Design in 1993 (Gauzin-Müller, Favet and Purver 17). A theory of sustainable architecture based largely on high-tech solutions is proposed by architect Richard Buckminster Fuller years ago. According to Fuller, technology brings radical changes to human society and will continue to do so, which leads him to espouse design principles that maximize technology in order to reduce waste and pollution (Robertson 48). Ruller's legacy motivates high-tech designers. Some of the outstanding projects are Beijing Airport and Caja Madrid Tower both designed by Norman Foster in 2008 and 2009 respectively. Various techniques have been used in these projects in order to support sustainability such as double skin glazed facades and recyclable steel structures.

(http://www.fosterandpartners.com/Projects/1177/Default.aspx; cited 27.02.2009)

**Figure 4** Beijing Airport designed by Norman Foster (2008)

(http://www.fosterandpartners.com/Projects/1179/Default.aspx; cited 27.02.2009)

**Figure 5** Caja Madrid Tower designed by Norman Foster (2009)

There are also critiques about technological approach. John Farmer, for example, criticizes high-tech design solutions. He believes technology "implicates the building with the very problem that underlies the environmental crisis" (40). Moreover, the universal application of high-tech materials and equipment makes sustainable architecture loose the connection with its climatic consideration and the concept of local material utilization (206). This critique under estimates the fact that there are conditions that high-tech systems and materials can be used in conjunction with the consideration of climate and local material use. For example the construction on a high-tech building a windy land by can benefit from this wind and produce energy using wind tribunes.

This study stands for a technological approach to develop sustainable environments. It is a fact that science and technology have created environmental problems; however, these problems can be solved again with a scientific understanding and better technologies. This is not to neglect that a low-tech approach to architecture supports sustainability in some aspects. It is significant to consider factors of both traditions and technologies, and their appropriateness in specific situations. Sustainable architecture can be achieved by using “the best of the old and the best of the new” (Lechner 5), which means that the combination of modern science and technologies with traditional ideas which respond to environmentally sustainable architecture.

In addition to the low-tech and the high-technology approaches, Kibert proposes another approach to sustainability in architecture, the biomimetic approach (Kibert 367-68). The word biomimicry is derived from two Greek words, bios which means life, and mimesis which means to imitate. Biomimicry is a discipline that studies nature's best ideas and imitates them to solve human problems. Applications range widely from architecture, product design and engineering to software development, communication systems and organizational evolution.

The concept of biomimicry goes back to humans in ancient times that have used it to form primitive huts inspired by natural forms. Modern architects are regularly inspired by the organic forms and the curves of the nature; an example to this is the tendrils, and floral motives of Antoni Gaudi and Art Nouveau buildings. Scientists and technologists have been imitating nature for years to foster innovations in engineering.

The concept has started to be used frequently by Otto Schmitt. In his article "Some interesting and useful Biomimetic Transforms" published in 1969, Schmitt argues that nature provides useful models that can be used in science and engineering to solve human problems. The concept has developed in 1997 with Janine Benyus's revolutionary book *Biomimicry: Innovation Inspired by Nature*. In her book, Benyus describes, "a new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems, e.g. a solar cell inspired by a leaf" (30). Biomimicry can be applied to architecture at various levels; form, functions or entire ecosystems. In architecture, mimicking nature's form is now a current issue. Bob Berkebile and Jason McLennan summarize biomimetic understanding as; "From my designer's perspective, I ask: Why can't I design a building like a tree? A building that makes oxygen, fixes nitrogen, sequesters carbon, distils water, builds soil, accrues solar energy as fuel, makes complex sugars and food, creates microclimates, changes colors with the seasons and self-replicates. This is using nature as a model and a mentor, not as an inconvenience. It is a delightful prospect” (1).

Kibert emphasizes that “[b]iomimicry could be called a ‘strong ecological design,’ because it advocates using exactly the same materials and processes utilized by nature” (367). He describes the general rules, starting with material choice. He says, “[i]f the material or process is not present in nature, it should not be used in the human sphere. Materials produced by nature are produced locally, breakdown when their useful life is expended, and the breakdown products are used by nature in a continual process of constructing new materials. Nature does produce ‘toxins’ as opposed to the ‘toxics’ often created in industrial processes. The difference is that toxins are produced in small quantities, for defensive purposes, and breakdown into raw materials for recycling by nature. In contrast, toxics are generally persistent, are not used for defensive purposes, and may dissipate around the planet, with negative consequences virtually everywhere” (Kibert 367).

Biomimicry can be used by the technological approaches to sustainable architecture to generate energy from sunlight and to form strong and lightweight materials. Chrissna du Plessis describes a future built environment based on biomimicry. This built environment contains solar energy collectors made of biologically-based or created proteins, a strong lightweight structure constructed by attaching sections to each other with a super strong adhesive which is based on a material as mussels produce and a building membrane that allows energy and ventilation flow. This building membrane and other components of the environment are proposed to be self-repairing, self-regulating and self-cleaning. Finally, at the end of its lifetime, the organic components of the building are proposed to be digested and the inorganic ones recycled. The applicability of this biomimetic approach to architecture will increase with the developments in technology. Buildings that have the features and structures mentioned above will symbolize the new generation buildings.

### 2.3. Sustainable Architectural Properties

While considering the criteria for sustainable architecture, it is necessary to mention some important concepts such as embodied energy and life cycle assessment. Embodied energy is the energy required to extract, process, package, transport, install, and recycle or dispose materials that make up a building. It refers to the total energy consumed in the process of raw materials, manufacturing, transportation, installation, maintenance and ultimate reuse of a product. Up to 70% of the total energy invested in a building's construction is embodied in the material. This includes the energy of the fuel used to power the harvesting or mining equipment, the processing equipment and the transportation devices that move raw material to a processing facility (Kim and Rigdon 25)

The development of sustainable buildings has been evaluated in many dimensions including the life cycle assessment. The life cycle approach to design engages with ecological, social, and economic impacts understood across the lifetime of a product, process, material, technology or service (Braden 13). In architecture, this means that these impacts must be considered throughout the life span of the building, from site selection, design and construction to operation, maintenance and demolition. The life cycle can cover the extraction of resources, the manufacturing process, installation in a building and the item's eventual disposal (Fuller 1-3). In *Sustainable Construction Green Building Design and Delivery,* Kibert gives a brief definition of life cycle assessment. "Life-cycle assessment is a method for determining the environmental and resource impacts of a material, a product, or even a whole building over its entire life. All energy, water and materials resources, as well as all emissions to air, water and land, are tabulated over the entity's life cycle" (30).

Life cycle analysis provides a systematic framework for tracking technologies, materials and assemblies from "cradle to grave" (or "cradle to cradle")[3] : "Providing a matrix for assessing environmental impact during the design process, the framework addresses sourcing, processing and manufacturing, use and maintenance, reuse, recycling, and disposal" (Wann 148).

Kibert emphasizes the importance of life cycle assessment for material selection. He also mentions that life cycle assessment is an approach that examines all selection decisions "rather than being simply an item's performance in the building" (30). He writes about the steps that life cycle assessment is compromised of such as inventory analysis, impact assessments and interpretation of the impacts. He states, "[E]nvironmental performance is generally measured in terms of range of potential effects" (248). Besides the embodied energy of a building's products and materials that are invested in the extraction, manufacture, transport and installation, Kibert

[3] William McDonough and M. Braungart state in their book *Cradle to Cradle,* "Imagine what you would come upon today at a typical landfill: old furniture, upholstery, carpets, televisions and plastic packaging. Resources are extracted, shaped into products, sold, and eventually disposed of in a 'grave' of some kind, usually a landfill or incinerator. Cradle-to-grave designs dominate modern manufacturing. According to some accounts more than 90% of materials extracted to make durable goods in the United States become waste almost immediately."

gives importance to operational energy that a building needs to run over its lifetime to keep continuing its life. He adds, “[f]or the average buildings, the operational energy is far greater than the embodied energy, perhaps 5 to 10 times higher. Consequently, the operational stage has far more energy impacts than those up through the construction stage. For other effects, however the effects of the stages up through construction can be far greater. Toxic releases during resource extraction and manufacturing process can be far grater than those occurring during building operations” (249). Kibert finally sums up by emphasizing that the clear result for the entire life cycle of the building is not just the construction process. Sustainable architecture consists of environments that have been protected and taken into consideration before, during, and after construction.

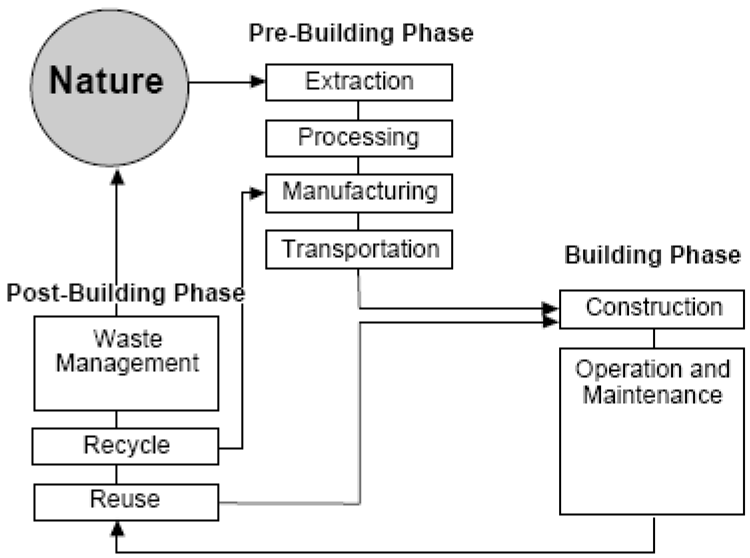



**Table 1** The three phases of life cycle assessment and contribution (Kim and Rigdon 8)

As it is seen in the table above there are three building phases in which the sustainability of a building can be evaluated. The pre-building phase includes site selection, building design, and building material processes but not construction. The environmental effects of the building's design, orientation, and impact on the landscape, and materials used are examined under this phase. Building Phase refers to the stage of a building's life cycle when a building is physically being constructed and operated. The construction and operation processes for ways to reduce the environmental impact of resource consumption are examined under this phase. (Kim and Rigdon 8) The Building Phase refers to a building material's useful life. This phase begins at the point of the material's assembly into a structure, includes the maintenance and repair of the material, and extends throughout the life of the material within or as part of the building. Post-Building Phase begins when the useful life of a building has ended. In this stage, building materials become resources for other buildings or waste to be returned to nature. Ways to reduce construction waste by recycling and reusing buildings and building materials are examined under this phase (Kim and Rigdon 22-27).

Except the sustainability evaluation phases of a building, there are also other evaluation criteria that a building should fulfill. Sustainable architecture focuses on different evaluation criteria such as, site, energy resources, energy consumption, water use and finally material (Kicklighter and Kicklighter 50). These categories can vary in detail according to context. Clois Kicklighter and Joan Kicklighter outline these criteria with little differences as, site selection and building orientation, construction methodology, material selection, energy generation and consumption, water consumption and waste management (52). These categories actually overlap. For instance, building orientation often affects overall energy consumption. Material selection influences the construction methodology employed. Water recycling strategies may increase energy demands. Although consideration of these categories separately allows for easier discussion of more specific strategies, their detailed analysis is not necessarily a part of in this study. This section will examine some of these categories, selected from those mentioned. These categories are thermal insulation, construction methodology, maintenance, energy sources and natural light and ventilation[4].

***Natural Light and Ventilation.*** Buildings consume most of the energy during their operation, in heating, lighting and cooling. The energy consumed by a building in these operations cannot be recovered. The building design, which utilizes natural light and ventilation, will lead to conserving energy, and reducing cooling and lighting energy consumptions. Reduced heating and cooling loads require smaller HVAC equipment, and the initial need for energy for the equipment will be smaller (Lechner 12). Buildings should be dynamic rather than static. The ventilation and lighting of buildings are accomplished not only by mechanical equipment but also mainly by the design of the building itself. Mechanical equipment responds to the continually changing heating, cooling, and lighting needs to create sustainable buildings.

***Energy Generation.*** Sustainable design deals a very large set of issues, and energy issues are a large subset. The environmental impacts of energy consumption by buildings occur primarily away from the building site, through mining or harvesting energy sources and generating power. This challenge brings the consideration of reducing the demand of expensive and environmentally damaging sources like fossil fuel energy. Renewable energy sources such as solar, wind, water and geothermal energy systems are recent alternative technologies. These innovative energy

[4] As mentioned sustainability criteria covers some important categories such as the water consumption, waste management and materials selection. However, these categories have eliminated with the reason that this study combines these categories do not overlap with the main concept.

systems may enable buildings to generate at least as much energy as they consume (Edward 58).

***Maintenance.*** Material selection is one of the major issues to design a sustainable environment. Materials should include several aspects. These are; using recycled material, easy recycling, long lifespan, manufactured and delivered with a minimum amount of energy, be manufactured without using dangerous materials and requiring minimal maintenance. This may be equivalent to several years of operating energy. These aspects are related to the life cycle of a material.

As mentioned earlier, life-cycle assessment is a method for determining the environmental and resource impacts of a material, a product or even a whole building over its entire life. In the life cycle assessment, in addition to the embodied energy of a material's operational energy also has crucial importance. Building materials vary with respect to how much energy is needed to produce them. Materials with higher embodied energy usually have higher environmental impacts due to their energy consumption. The greater an embodied energy of a material the greater the amount of energy required producing it, results with more severe ecological consequences. In contrast, some products that have easy maintenance will have lower embodied energy over time. In addition, embodied energy of certain materials become lower after the installation due to their property of easy maintenance. New products require more energy so a material with an easy maintenance property will require less energy. Maintenance is related to the operational energy of the material during the building phase (Kibert 44).

***Thermal Insulation*.** A major challenge for designers while designing sustainable buildings is to create buildings that use less energy, in other words, buildings with low energy profile. Energy consumption is one of the greatest concerns for architects. Thorough insulation is one of the best ways to reduce energy consumption and building operating costs. Edna Shaviv mentions that the main aim of energy conservation in buildings is "to minimize the required energy for heating, cooling and lighting, while relying very little on energy from polluting fuels" as much as possible (463). High-performance windows and wall insulation prevent both heat gain and loss. Reducing such heat transfer reduces the building's heating and cooling loads and thus its energy consumption (Cohen 30).

***Easy Installation*.** Buildings consume energy not only in their operation for heating, lighting and cooling, but also in their construction. The influx of construction equipment and personnel onto a building site and process of construction itself disrupts the local ecology. Construction and destruction often require large amounts of energy for processes, ranging from moving earth to welding. Materials that are easily installed using conventional tools also reduce overall waste from constructing. The sustainable design strategies focus on reducing construction waste because minimal construction waste during installation reduces the negative effect construction on the environment (Kim and Rigdon 5).

These five categories will lead a determination of the selection of smart materials in the next chapter. The context of these categories will cover the determination of some concepts such as embodied energy and life cycle assessment.

## 3. SMART MATERIALS

In prehistoric times, humans have had access to only a very limited number of materials that exist naturally: stone, wood, clay and so on. In time, the discovery of new techniques for producing materials leads to the discovery of new materials with improved properties. Furthermore, it is discovered that the properties of a material could be altered by heat treatment or by adding substances. In *Materials Science and Engineering,* William D. and Jr. Callister mention about the change of the materials' utilization after the discoveries of techniques for producing materials and add that the utilization was "a selection process involving deciding from given, rather limited sets of materials to the best suiting one for an application by virtue of its characteristics" (1). This new area of science and technology gave rise to the evolution of designed materials with certain desired properties. Some of these designed materials include bronze, steel and plywood. Parallel to other technologies developments, the range of possibilities in material science has increased rapidly day after day. In his, book *Transmaterial: A Catalog of Materials that Redefine our Physical Environment*, Brain Brownell relates this rapid acceleration of material science with Moore's Law, which states that "computational power follows an accelerated curve" (Brownell 7). Another promotional factor is "the NASA effect." Innovations, which have been developed for aerospace or military applications are presented for consumer use.

There are three different historical periods of the developments of architectural materials. The first period comprises the time until the antiquity. During this period, materials are used with as they exist in nature. The second period covers the time between the antiquity and the 19th century. During this period, since the material industry has not improved enough, materials are used with their natural properties; however, they are used to form new complex shapes such as arches, domes and vaults as a result of new construction techniques. By the end of 19th century, new materials start to take place in architecture, like iron and glass parallel to mechanization and further developments in construction. Since then, with the help of improving technologies, the structure and the appearance of the materials are manipulated more than their having different forms. This change enables to create new materials with new properties. Furthermore, the improvements in material science also provide new techniques for material production such as composite materials, which are composed by layering several materials (Erinç 10-18).

One of the new concepts, which has been introduced as a result of the new technologies, is "smart materials." Over the past 10 to 20 years, a number of materials have been given the term 'smart' based on their material properties. Although these materials are commonly referred to as smart, this is debated among scientists. There are several adjectives that cause confusion about the concept of these new materials such as, intelligent, adaptive or active materials. All of these expressions have been used interchangeably to describe the research in this field. Some researchers believe that the term "smart" has been misused and that it is more accurate to call them "adaptive" or "active." Others are not sure how smart the materials are, but see a progressive increase in the responsiveness of these materials. To propose a clear definition, it is necessary to give the dictionary definitions of these adjectives. As to *Webster's Ninth New Collegiate Dictionary,* 'smart' means, "having or mental alert, bright knowledgeable" whereas 'Intelligent' means; “the ability to learn or understand or deal with new or trying situations; the ability to apply knowledge to manipulate one’s environment or to think abstractly.” Adaptive is defined as “having or showing the ability to make” and active is “quick in physical movement; requiring vigorous action or exertion; engaged in an action or activity.”

As to their dictionary definitions, all these adjectives have different meanings. Spillman Sirkis and Peter Gardiner explain these that “[I]ntelligent and smart address mental activity in reality; while adaptive, active […]on the other hand, address physical activity. The difference between them lies mainly in the type of activity. “Active” simply means that physical activity is occurring, whereas, “adaptive” implies that the activity results in only modifications to existing configurations” (248). In addition, they comment on the conflict between the dictionary definitions and used purposes of these adjectives and they criticize and indicate the problem of the use of these adjectives interchangeably. They say, “terms such as smart, intelligent and adaptive are commonly used to refer to the same level of functionality” (248).

The dictionary and definitions technical meanings of these adjectives are different from each other. The dictionary definitions represent something new. ‘Intelligent materials’ are special materials which have the ability to respond to the non-programmed situations more than to adapt to unexpected environmental conditions (Beck & Gobin 18). In other words, these materials are able to react and to adapt new environmental conditions. They are able to change their properties according to specific environmental stimulus. However an ‘intelligent material’ “involves using past history to develop a world model, predicting future conditions and then basing actions upon not only upon conditions as they are but also upon expected future conditions as predicted by the model" (Sirkis and Gardiner 253). On the other hand, a 'smart materials' bases its actions by optimally adapting to present conditions. "[S]ince conditions are continually changing, the smart structure will never be optimized for present conditions (unless the environment is essentially static), but rather for those of the recent past" (Sirkis and Gardiner 253). This section focuses on four groups of selected smart materials, their properties and types.

Although discoveries of smart materials have been made about 50 years ago, their application in engineering and commercial fields is a new trend. A variety of smart materials already exists, and they are being further researched. Some everyday items are already produced using smart materials and the number of applications is growing rapidly[5]. The story of smart materials has started in the late nineteenth century when the Curie brothers discover that several natural materials, including quartz and Rochelle salt, exhibit interesting properties. Interest in these types of special materials has increased in the early twentieth century due to the onset of World War I, which has laid the ground for new inventions like the prototype of a sonar system. World War II has stimulated even more advances in new materials and devices. These advances lead to new discoveries in communication like the radio, as well as other applications, such as phonograph cartridges for record players (Donald 5-10). In the early 1960s, Donald Stookey has developed a glass named "Corning Glass" that darkens when exposed to light and lightens when the light is withdrawn

[5] Examples of contribution of smart materials in consumer goods; 1. Vibration reduction in sporting goods. A new generation of tennis rackets, golf clubs, baseball bats and ski boards has been introduced to reduce the vibration in these sporting goods, increasing the user's comfort and reducing injuries. 2. Noise reduction in vehicles. Smart materials technology-based products have been used by mechanical engineering to counter noise in vehicles, neutralize shaking in helicopter rotor blades, or nullify or at least diminish vibrations in air conditioner fans and automobile dashboards.

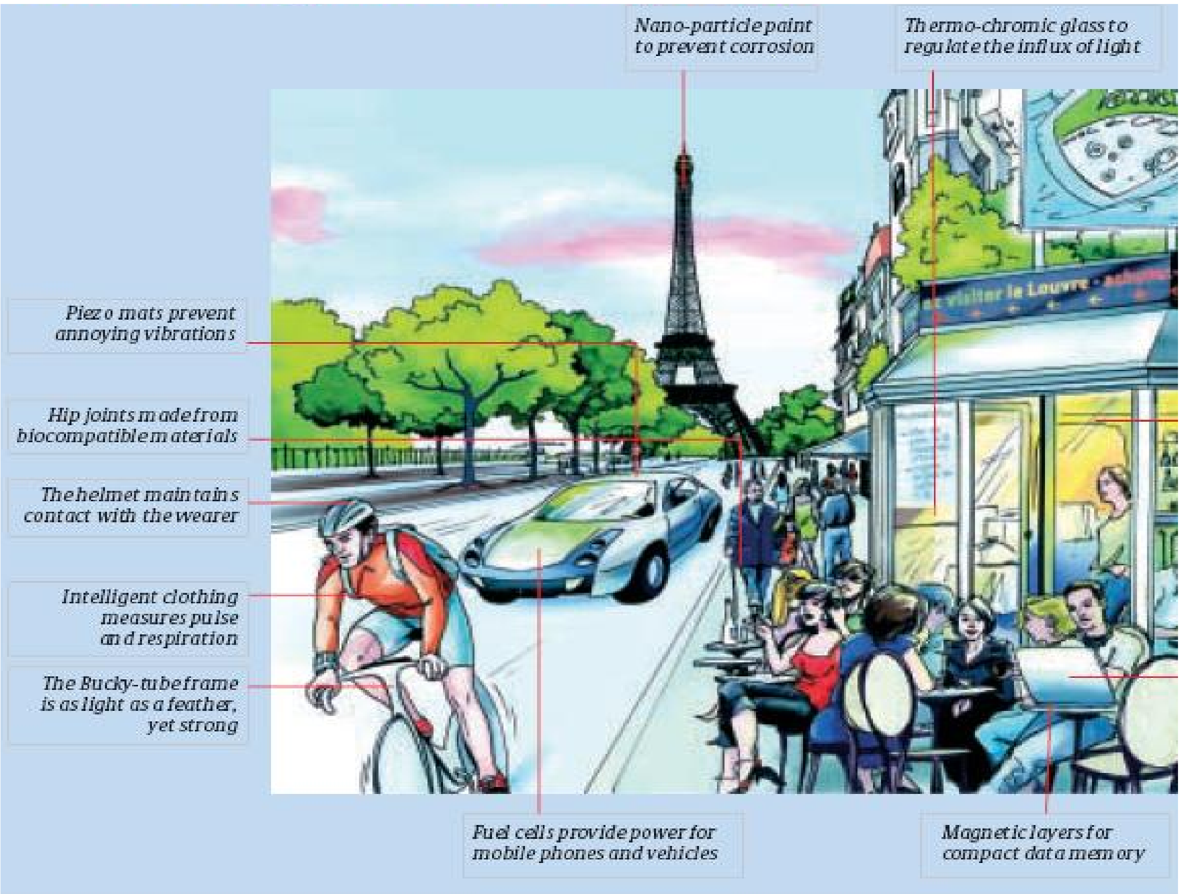
(Geiser and Commoner 249). During the 1970s, NASA has started research on materials that could sense and display potential faults, cracks, fatigue, or excessive strains in structural materials. The idea is to create airplanes with smart skins that could sense aeronautical conditions, such as air speed, temperature, and pressure, and detect early indications of potential failure (Geiser and Commoner 237-38).

According to Addington and Schodek, these special materials were firstly called 'smart' in 1992 in "Smart Skis and Other Adaptive Structures" article in *Mechanical Engineering-CIME* journal when the first smart material emerged commercially in snow skis' (1). In *Smart Materials and Technologies in Architecture* Addington and Schodek, mention two definitions of smart materials. The first definition is made by NASA. They define these materials as "materials that remember configurations" as substances and can perform these materials under different inputs and can be qualified by their molecular structure. The second definition, which they get from the *Encyclopedia of Chemical Technology,* is about materials' sensation of environmental inputs and their processing of and reaction to sensory information. This definition differs from the first one by evaluating these materials as performing "a series of actions" which can be composite, singular or combination of different materials. The first definition refers to 'substances' which are identifiable and quantifiable by their molecular structure. Addington and Schodek's proposal of five characteristics for materials or composites which would quality as smart are: <u>"immediacy"</u>: they respond to environmental changes in real-time, <u>"transiency"</u>: they respond to more than one environmental state, <u>"self-action"</u>: their intelligence is internal to the material, <u>"selectivity"</u>: is their response is discrete and predictable and finally <u>"directness"</u>: their response is local to the activating event (Addington and Schodek 8-10).

Alex Ritter gives another definition of smart materials in his book entitled *Smart Materials in Architecture, Interior Architecture and Design*. “These materials, substance and products have changeable properties and are able to reversibly change their space or color in response to physical and/or chemical influences, e.g. light, temperature or the application of an electrical field” (Ritter 26). Although, Ritter and Addington and Schodek cite different definitions for smart materials, their definitions are similar in principle. Basically, there is no standard definition for smart materials. The most commonly accepted definition is that the term generally designates a material that changes one or more of its properties in response to an external stimulus in a predictable and useful manner (Harrison and Ounaies 1).

Smart materials have found their way out of laboratories and into industrial applications for the previous decade. They are currently used for a growing range of commercial applications, including noise and vibration suppression (noise-canceling headphones); strain sensing (seismic monitoring of bridges and buildings) and sensors and actuators (such as accelerometers for airbags).

In her interview about the utilization of smart materials published in *Architecture Boston* Magazine, Addington says “They don’t replace the window; they don’t replace the wall. What they do is *activate* these components and systems.” Addington answers the Interviewer’s question about the application method of smart materials in an existing system saying, “…smart materials are very powerful but very small, the ideal use of them would be in ways in which they’re not visible to us... When you suggest spraying the smart material on or using it as a film, you are still thinking in terms of a building scale. So, how do you take these small actions? You could have a tiny little heat sink that would completely control heat transfer through the wall almost invisibly, with a few resistance wires." As understood from Addington's comments, the basic actions and behaviors of smart materials enable them to be integrated with different smart systems and products. Single utilization of smart materials does not provide clear profits in many cases. Many common sensors and actuators are based on the use of smart materials.




(Nesrin Hasırcı. Intelligent Materials (Smart Materials), presented at IEU, Dec. 29, 2008)

**Figure 6** Possible application areas of smart materials.

In *Smart Material Systems and MEMs: Design and Development Methodologies,* Vijay Varadan gives a detailed indication of various areas for the application of smart materials, from mechanical tools and health monitoring to aircrafts and the computer industry. As this study analyzes these materials from an architectural point of view, it will be enough to briefly indicate their application purposes in construction. Smart materials are been using to improve safety, security and energy control systems. They also contribute in the glazing to increase isolation in ventilation and air conditioning systems to reduce costs (Varadan 14-15).

### 3.1. Types and Properties of Smart Materials

Smart materials obtain their unique properties through their “awareness.” Awareness enables the material to examine its condition or environment, change shape, repair itself, or perform other functions that technological developments allow. Smart materials have several interesting properties. Addington and Schodek describe the property difference between regular and smart materials as follows: "Most everyday materials have physical properties which cannot be significantly changed; for example if oil is heated it will become a little thinner, whereas a smart material with variable viscosity may turn from a fluid which flows easily to a solid” (Addington and Schodek 24).

There are various types of smart materials and accordingly they have different properties. Some of the smart materials have the ability to change shape or re-size simply under a small amount of heat. Alternatively, near a magnet some materials can change their form from a liquid to a solid almost instantly. Consequently, scientists group smart materials in various ways. While some sources categorize smart materials according to their atomic structures, other classifies them as to their properties. The table below indicates some of the specific smart materials, the stimulus that they react and responses that they show.

| Response / Stimulus | Electrical | Magnetic | Optical | Thermal | Mechanical |
|---|---|---|---|---|---|
| **Electrical** | | | Electrochromic<br>Electroluminescent<br>Electro-optic | Thermoelectric | Piezoelectric<br>Electrostrictive<br>ER fluids |
| **Magnetic** | | Magnetostrictive | Magneto-optic | | MR fluids<br>Magnetostrictive |
| **Optical** | Photoconductor | | Photochromic | | |
| **Thermal** | | | Thermochromic<br>Thermoluminescent | | Shape Memory |
| **Mechanical** | Piezoelectric<br>Electrostrictive | | Mechanochromic | | Negative<br>Poison Ratio |

**Table 2** Stimulus-response matrix for selected smart materials (Ghandi and Thompson 41)

Addington and Schodek divide smart materials into two groups. The materials in the first group undergo changes in one or more of their (chemical, electrical, magnetic, mechanical or thermal) properties in direct response to a change in external stimuli in the surrounding environment. For example, a photochromic material alters its color in response to a change in the amount of ultraviolet radiation on its surface. A type two smart material, on the other hand, transforms energy from one form to another. This class involves materials with the following types of behavior: photovoltaic, thermoelectric, piezoelectric, photoluminescent and electrostrictive (Addington and Schodek 15-45). There is a difference between the two types. Contrary to ‘type 1’ smart materials, ‘type 2’ materials are “made up of several more basic materials that are constituted in a way to provide a particular type of function” (Addington and Schodek 17) . For example, a photovoltaic cell consists of different layers of different materials and to obtain an adequate operational voltage the cells must be connected in series to form modules (Messenger and Ventre 182).

Ritter analyses smart materials under three categories according to their properties, namely property-changing, energy-exchanging and matter-exchanging smart materials. Alternatively, John Fernandez classifies smart materials under six categories; metals, polymers, ceramics, composites, biomaterials and loam (46-182). In their books, Ritter, and Addington and Schodek do not examine all of these smart materials in detail. They chose specific ones which are already in use, ready to use or applicable in architecture. This study follows the same approach and some smart materials have been chosen according to specific criteria will be discussed here. As mentioned before, the main concern of this study is the ecological use of the smart materials in architecture. To deal with this issue effectively, some of the leading smart materials, which are related with the main topic, will be analyzed in this chapter under four classes according to their properties. These categories include shape changing, energy generating, self-maintaining and high isolation smart materials. These selection criteria and the material categories have been composed through development of the thesis with a continuous process. The knowledge obtained from the research on smart materials and sustainability help to form the criteria and categories by making addition and extrusions. There are three basic questions, which form the criteria, and categories, what is the property of the material, are these properties can contribute to sustainability and if it can contribute how? Though the answers the two important table is composed. First, one is stated below and the other one takes place in the next chapter. The table below indicates the chosen smart materials, the group that they belong to, the input and the output that they exhibit.

| PROPERTY | GROUP | MATERIAL | STIMULUS/INPUT | REACTION/OUTPUT |
|---|---|---|---|---|
| **Shape Changing Property** | Thermostrictive Smart Materials | Shape Memory Alloys | temperature | Mechanical (bi-directional shape changing) |
| | | Shape Memory Polymers | | |
| | Electrostrictive Smart Materials | Electroactive Polymers | electricity | |
| **Energy Generating Property** | Energy Exchanging Smart Materials | Photovoltaic | radiation energy (UV wave from Sun) | Electrical current |
| | Electricity Generating Smart Materials | Piezoelectric | mechanical energy (strain) | |
| **Self Maintaining Property** | Microcapsulation Method | Laminated coating on different materials | Crack | Self healing action |
| | Microvascular Networks Method | | | |
| | Lotus-Effect | Coating as a paint | Dirt + water | Self-cleaning action |
| | Photocatalysis Effect | Coating on glass, ceramic, membrane | Dirt + sun + water | |
| **High Insulation Property** | Nanostructured materials | Aerogel | Temperature changes between surfaces of the material | Insulation between surfaces |
| | Polymer | ETFE | | |

**Table 3** Types and properties of smart materials

### 3.2. Shape Changing Materials

Shape changing materials are able to change their shape reversibly under a stimulus, such as the effect of light, pressure, heat, electricity or magnetism. The shape or the dimension of the material, or both parameters can change. Ritter defines this change in shape as follows: “The inherent properties of these smart materials depend on different principles behind their deformation. Depending on the distribution and arrangement of the sensitive components and a basic geometric shape, changes may take place in all dimensions to equal and unequal extents” (Ritter 46).

Shape changing smart materials have different sub-categories according to the stimulus to which they react. Ritter divides these materials into 6 categories: photostrictive smart materials, thermostrictive smart materials, piezoelectric smart materials, electroactive smart materials, magnetostrictive smart materials and chemostrictive smart materials. Addington and Schodek define shape-changing materials in a more general way. “Most shape changing materials move from one position to another” (141); they do not specifically classify these materials but divide them according to the change they exhibit. Bending or striating as shape memory alloys, elecrtostrictive and piezoelectric materials do, twisting or untwisting as shape memory alloys do, constricting or loosing as magnetostrictive materials do and swelling and shrinking as polymer gels do. In this study, some of the shape changing materials will be examined according to the stimulus to which they react; temperature and electricity.

Ritter classifies piezoelectric smart materials under shape changing smart materials but analyzes them under electricity generating smart materials for the reason of the piezoelectric effect that these materials exhibit. Piezoelectric smart materials generate an electrical charge as a result of shape deformation under a mechanical load (Ritter 154). For the same reason, Piezoelectric Smart Materials will be examined in the same chapter as the electricity generating smart materials.

### 3.2.1. Thermostrictive Smart Materials

Thermostrictive Smart Materials show a physical change when external thermal stimuli are presented. This category contains different kinds of smart materials[6] but the most widely known kinds are the ‘Shape Memory Alloys’ and ‘Shape Memory Polymers’ that exhibit shape memory effect.

Addington and Schodek explain the ‘shape memory effect’ by giving examples from commercial applications which simplify its meaning: “Perhaps surprisingly, eyeglass frames that are amazingly bendable, medical stents for operating on arteries that are implanted in a compressed form and then expand to the right size and shape when warmed by the body, tiny actuators that eject disks from laptop computers, small micro valves and a host of other devices, all share a common material technology. The interesting behavior of each of these devices relies upon a phenomenon called the ‘shape memory effect’ that refers to the ability of a particular kind of alloy material to revert, or remember, a previously memorized or present shape” (105).

[6] Other Thermostrictive Smart Materials are Thermal Expansion Materials, Thermobimetals and thermobicomposite materials.

The first recorded observation of smart material was made in 1932 on gold-cadmium. In 1938, the phase transformation was observed in brass (copperzinc). In 1962, Beehler and his co-workers found the transformation and attendant shape memory affect in Nickel-Titanium. They named this family of alloys nitinol[7]. A few years after the discovery of Nitinol, a number of other alloy systems with the shape memory effect were found. Nitinol, which is a mixture of two different metals, nickel and titanium, has the property of shape memory effect (Otsuka and Wayman 3).

Shape memory alloys are metals that "remember" their original shapes. They "change shape, stiffness, position, natural frequency, and other mechanical characteristics in response to temperature fields" (Rogers 155). Materials that exhibit shape memory only upon heating are referred to as having a one-way shape memory. Some materials also undergo a change in shape upon re-cooling. These materials have a two-way shape memory. As referred to above, in the words of Addington and Schodek, today, shape memory alloys have been implemented in everyday applications such as eyeglass frames that are resistant to bending (Rogers 155).

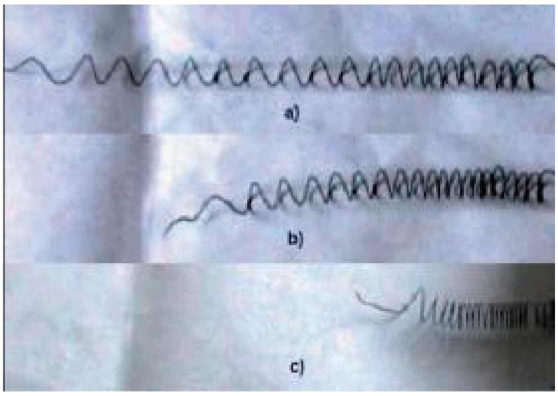



**Figure 7** Phases of Shape Memory Alloy under heat (Stylios and Wan 325)

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[7] Nitinol stands for Ni (nickel) and Ti (titanium).

Shape memory alloys are not the only materials that exhibit shape memory effect. Shape-memory polymers are dual-shape materials belonging to the group of 'actively moving' polymers responding to the environmental stimulation such as temperature change (Charlesby 198).

Shape memory polymers can be applied to textiles and garments to enhance the air permeability based on the change in free volume at different temperatures (Tobushi and others 136). Although they have been used and applied to textiles, most important application area for shape-memory polymers is in active medical devices and implants.

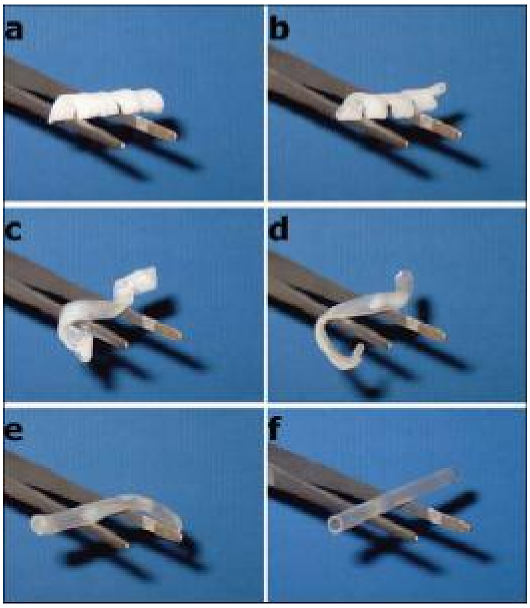


**Figure 8** Phases of Shape Memory Polymer under heat (Robert and Tirrell 488)

Shape memory Alloy and polymers have been used for military, medical, safety and robotics applications. There are many possible applications for shape memory alloys. Future applications are envisioned to include engines in cars and airplanes and electrical generators utilizing the mechanical energy resulting from the shape transformations. Shape memory alloys are also envisioned for use as car frames (Kauffman and Mayo, 6) shape memory alloys are "ideally suited for use as fasteners, seals, connectors, and clamps" in a variety of applications (Borden, 67).

### 3.2.2. Electroactive Smart Materials

Similar to thermostrictive smart materials electroactive smart materials also change their shape in response to electrical stimulus. This category contains but is not limited to electrostrictive paper[8], electrostrictive ceramics, electrostrictive graft elastomers[9], magnetostrictive tags[10] and magnetic shape memory alloys. Electroactive polymers are the most commonly applied ones.

Electroactive polymers are polymers “that are able to change their shape under electrical stimulation” (Ritter 66). There are many different application areas for electroactive polymers; however, because of the behavior similarity of these materials to biological muscles, they are commonly used to create “artificial muscles.” Electroactive polymers have emerged with great potential enabling the development of unique biomimetic devices (Bar-Cohen 7).

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[8] Generally, electrostrictive paper is composed of a multitude of discrete particles, which are mainly of a fibrous nature forming a network structure, an example of which is silver laminated paper, whereby two silver laminated pieces of paper with silver electrodes are placed on the outside surfaces. Upon electric voltage being applied to the electrodes, a bending displacement occurs (Ritter 66).

[9] Elastomer is a polymer consisting of two components, a flexible macromolecule backbone and a grafted polymer that can be produced in a crystalline form. The material exhibits high electric field induced strain combined with mechanical power and excellent processability (Ritter 66).

[10] Magnetostrictive tags are used to detect the damage in composite materials using a tagged material, which emits a magnetic signature that is proportional to the applied stress. The location of cracks is detected by local peaks in magnetic signature (Ritter 66).

### 3.3. Energy Generating Smart Materials

The properties of the smart materials introduced in this section are different from shape changing materials. Energy generating smart materials are able to produce different kinds of energy. They provide energy generally by exchanging from one type of energy to another, to electrical energy. These materials are examined under two categories according to their inputs and outputs: energy exchange and electricity generation.

The materials included in this chapter are actually made up of a combination of several materials, which are constituted to provide particular functions. These combinations can be determined as simple devices. With the reason of their design concept and application purpose, these devises are associated with the term 'material' (Addington and Schodek 17-18).

#### 3.3.1. Energy Exchanging Smart Materials

Energy exchange relies on a simple physics law, the "conservation of energy." The law of the conservation of energy states that the total amount of energy in an isolated system remains constant. Traditional or smart, all materials must conserve their energy. If the energy status of a material is, equal to the environment surrounds it, no energy can be exchanged or, in other words, the material is "in equilibrium." If the energy status is different, then there is a probable energy exchange. This property can be summarized as such: the energy, which is input into the material, output as a different kind energy (Addington and Schodek 95). Addington and Schodek explain how energy exchange occurs in materials: “All of the energy exchange materials involve atomic energy levels – the input energy raises the level, the output energy returns the level to its ground state. For example, when solar radiation strikes a photovoltaic material, the photon energy is absorbed, or more precisely, absorbed by the atoms of the material. As energy must be conserved, the excessive energy in the atoms forces the atoms to move to a higher energy level” (95). Materials, which cannot attain this new level, give an equivalent energy output. In most of the materials, this energy is in the form of heat. Differently, energy exchanging smart materials emit this energy by exchanging it into a more usable type of energy such as electricity or light rather than heat.

Energy exchanging smart materials, with one or two exceptions, are all composite materials. One of the most commonly used smart materials in this category is the Photovoltaics (PV). French physicist, Alexandre-Edmond Becquerel, first recognized the photovoltaic effect in 1839. However, it was not until 1883 that the first solar cell was built by Charles Fritts, who coated the semiconductor selenium with an extremely thin layer of gold to form the junctions (Nelson 2).

(http://www.pdchost.com/sites/TWFERM_733893/images/photovoltaic.jpg; cited 27.02.2009)

**Figure 9** A photovoltaic system

Photovoltaic materials are multi-layered composite units or commonly named cells that consist of layers of different materials. The PV solar cells convert sunlight directly into electricity through the use of semiconductors. Basically, PV cells are made of at least two layers of semiconductor material. One layer has a positive charge, the other negative. When light enters into the cell, some of the photons from the light are absorbed by the semiconductor atoms, freeing electrons from the cell's negative layer to flow through an external circuit and back into the positive layer. This flow of electrons produces an electric current.

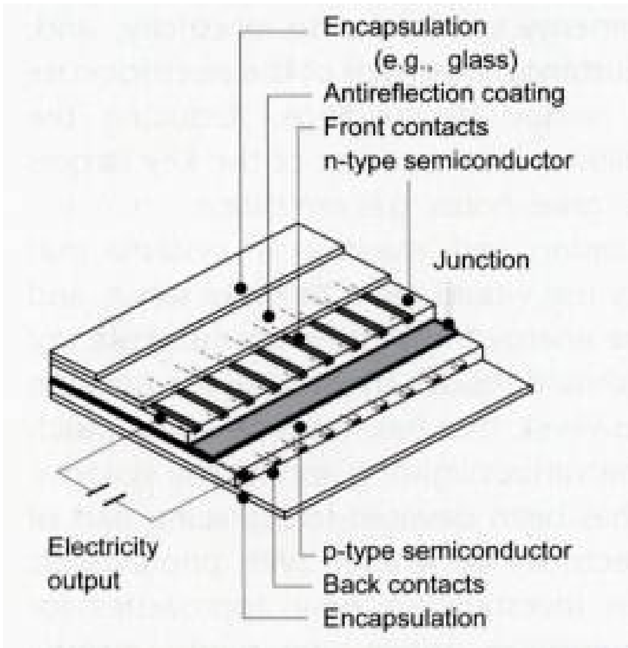



**Figure 10** Schematic layout of a photovoltaic cell (Addington and Schodek 182)

Each of these Photovoltaic cells produces 2 watts. The connection of cells in series is necessary in order to obtain adequate voltage. The cells are connected to each other to form a module and the modules are connected to each other in parallel to form an array. The resulting assembly is referred to as a PV system, solar panel or module (Markvart 24-39).

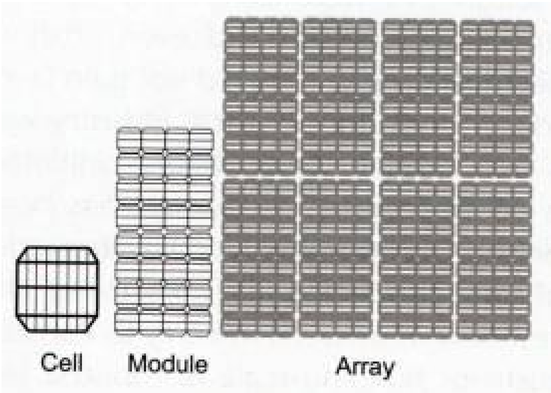



**Figure 11** Components of photovoltaic system (Addington and Schodek 182)

Modern solar cells are classified as three generations. The first generation cells contain crystalline silicon material, which captures light waves to convert sunlight into electricity. This generation dominates the commercial market. Silicon cells have a high efficiency, but very pure silicon is needed, and due to the energy-requiring process, the price is high compared to the power output. The second-generation cells are known as thin-film cells. Thin-film solar cells consist of plastic or other substrates coated with silicon or other photovoltaic material. "These cells experience a drop in efficiency when they are exposed to sunlight, and this effect is created in the intrinsic layers" (Nelson 177). The effect is produced by, instead of one layer, using several thinner layers. Finally, third generation solar cells are also called advanced thin-film photovoltaic. The third generation cells contain silicon nanostructures that use the infrared spectrum to produce electricity at night. Their efficiency relies on the use of several layers of solar cells with different band gaps in a stack. Each layer utilizes light with different wavelengths, and in this way, cells start to be more efficient (Nelson 177-78, 211-13, 289).

### 3.3.2. Electricity Generating Smart Materials

Electricity Generating Smart Materials are able to generate electrical energy in response to changes in temperature or pressure. thermoelectric, chemoelectric and piezoelectric smart materials are some of the sub categories. The most widely used type is the piezoelectric smart materials which will be disused in this section.

The electrical response to mechanical stimulation is called the piezoelectric effect. Piezoelectric smart materials produce an electrical current through an input of elastic energy. According to Harrison and Ounaies, the classic definition of piezoelectricity is the generation of electricity polarization in a material due to mechanical stress. Most of the piezoelectric materials are bi-directional in that the inputs can be switched and an applied electrical current will produce a deformation. The first experimental demonstration of a piezoelectric phenomenon has been published in 1880 by Pierre and Jacques Curie. Their experiment has consisted of a measurement of surface charges appearing on specially prepared crystals, which receive mechanical stress. They called this effect the piezoelectric effect (Addington and Schodek 103-04).[11]

Addington and Schodek summarize the piezoelectric property in materials as follows: “The phenomenon is based upon reversible energy conservation between electrical and mechanical forms that occurs naturally in permanently polarized materials in which parts of molecules are positively charged. Many naturally found crystals (e.g. quartz) possess this property, as do many newly developed polymers and ceramics.” “In piezoelectric materials, each cell or molecule is a dipole with a positive and

[11] In Greek "Piezo" means pressure.

negative charge onto either end. There is an alignment of the internal electricity dipoles. This alignment can result in a surface change, but this charge neutralized by free charges in atmosphere. A force is applied to the piezoelectric material that causes deformations to take place, which in turn alters to the neutralized state of the surface by charging the orientation of the dipoles. The reverse can also be achieved" (104).

There are two main types of newly developed piezoelectric materials, piezoelectric ceramics and polymer. Regarding their application, there are two main functions, shape control and vibration control. In addition, recently piezoelectric materials have been used as motors for hydraulic pumps for flow control. High-voltage sources, frequency standard and reduction of vibrations are some of the utilization areas of piezoelectric materials. They are also used in the music industry for acoustic instruments (George and others 56-57). The figure cited below demonstrates electricity generation of a piezoceramic with application of either compression or tension.

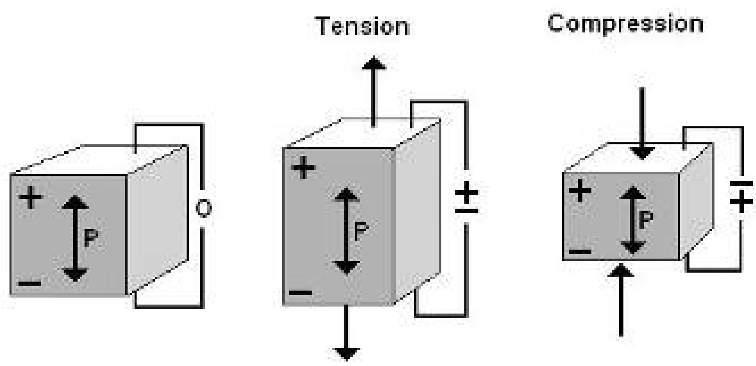



**Figure 12** Piezoelectric effect of a piezoceramic (Harrison 40)

### 3.4. Self Maintaining Smart Materials

Material science deals not only with research on these smart materials but also experiments with new technologies to improve the properties of existing materials'. One of these properties is the self-healing technology that has been recently introduced into the science world. Different from material science, several of these new technologies involve material researches to form new material with specific properties, which differ from smart materials being exhibited naturally such as self-maintenance. Two smart materials' properties enhanced though these technologies are examined in this section.

#### 3.4.1. Self Healing Smart Materials

In nature, damage to an organism invokes a healing response. This ability of nature to heal itself has inspired new ideas and new mechanisms in engineering. The ability to heal wounds is one of the remarkable properties of biological systems. Material design has led several interdisciplinary approaches involving chemistry, mechanics and materials processing to incorporate self-healing functionality in polymers and composites.

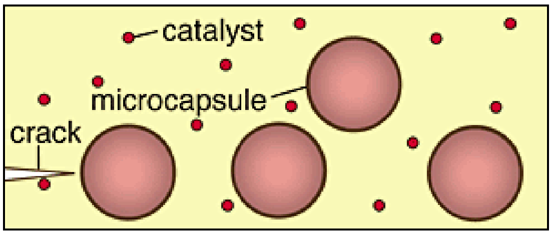
In her article "Modeling Self-Healing Materials" published in the *Journal of Materials Today,* Anna Balazs defines "self healing ability" as the biggest challenge in material science. She states, "[a] grand challenge in materials science is to design 'smart' synthetic systems that can mimic this behavior by not only 'sensing' the presence of a 'wound' or defect, but also actively re-establishing the continuity and integrity of the damaged area" (19). Such 'self-healing' materials would significantly extend the lifetime and utility of a vast array of manufactured items.

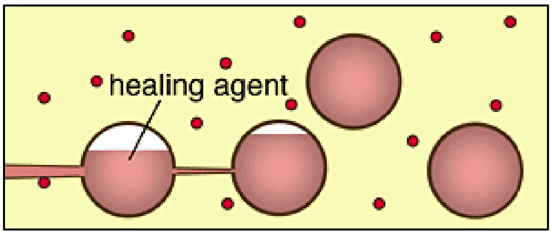
"The first clear demonstration of self-healing in an engineered materials system occurred in 2001 with the introduction of a microencapsulated healing agent and suspended catalyst phase in a polymer matrix" (Sottos, White and Bond 347). Since that time, rapid advancement has been made in the field following this conceptual approach, while alternative concepts have emerged in the scientific literature.

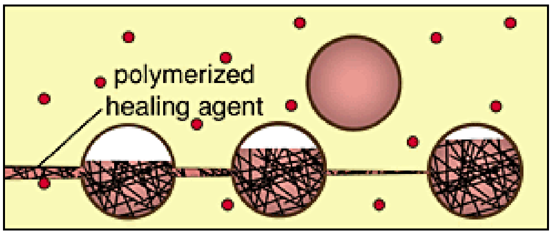
Self-healing materials are categorized in two groups, "Microcapsulation" and "Microvascular Networks," that have the same basic theory. Microcapsulation consists of encapsulated tiny bubbles filled with healing agent fluid that are spread throughout the material, which fix the micro cracks after damage. There are about 100 to 200 capsules per cubic inch. Microvascular Networks contain the same healing agent in a microvascular network. In the Microcapsulation method, there is a continuous supply of the healing agent, so the material can heal itself indefinitely. The microvascular Networks method provides a renewable source for the healing agents, which, therefore, enables repeated healing of fracture events and significantly extends the life of these materials (Sottos, Scott and Bond 347).

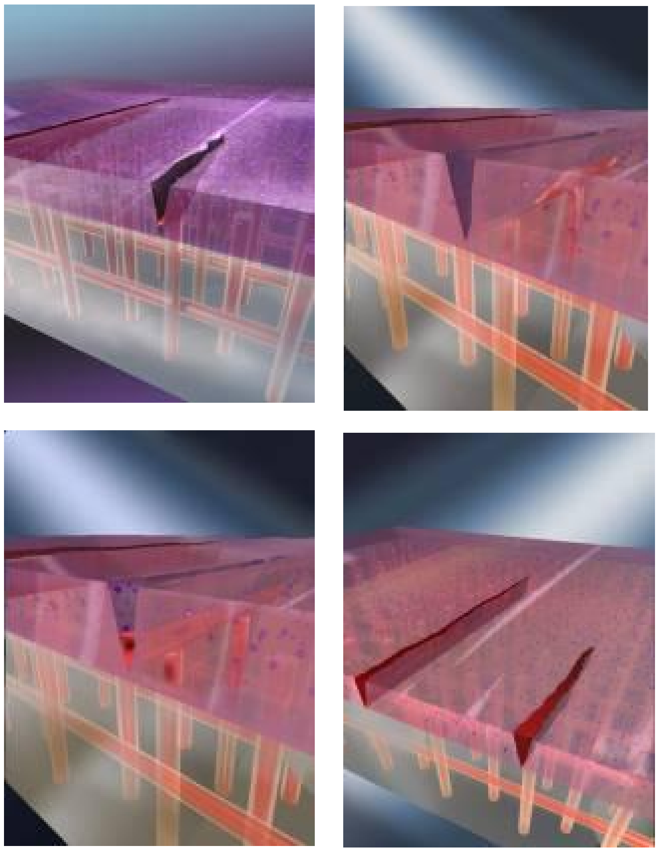
### 3.4.2. Self Cleaning Smart Materials

New materials are being discovered and developed everyday as a result of the knowledge of how to achieve molecular and atomic precision in the engineering of materials. Nanotechnology is the primary science promising new approaches to smart materials.

<table>
<tr><th>Microcapsulation</th><th>Microvascular Networks</th></tr>
<tr><td>
a) 

<br>
Figure 13 Cracks form in the matrix wherever damage occurs
<br><br>
b) 

<br>
Figure 14 The crack ruptures the microcapsules, releasing the healing agent into the crack plane through capillary action.
<br><br>
c) 

<br>
Figure 15 The healing agent contacts the catalyst, triggering polymerization that bonds the crack faces closed.
</td><td>

<br>
Figure 16, 17, 18, and 19 Cracks in a brittle coating are healed autonomously via a three-dimensional microvascular network embedded in the underlying substrate. The network contains a healing agent (red) which polymerizes after contacting the catalyst (purple) in the damaged regions.
</td></tr>
</table>

(http://www.autonomic.uiuc.edu/index.html-cited 20.03.2008)

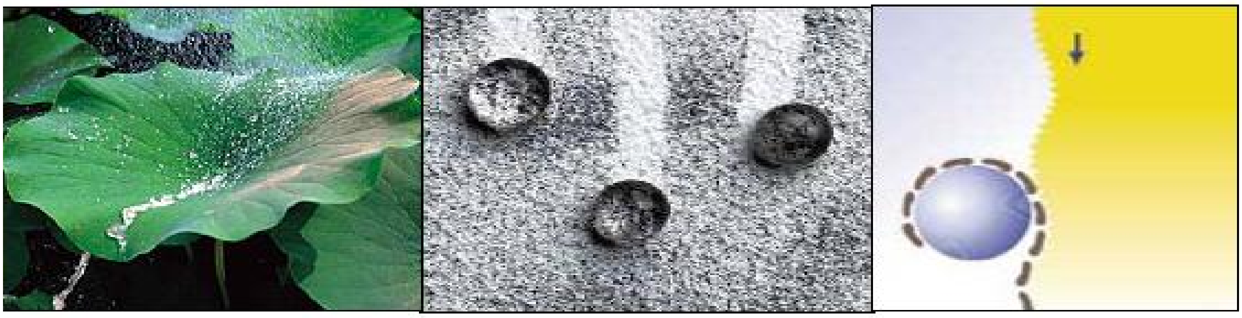
**Table 4** Self-healing technologies

The unit of nanometer derives its prefix nano from a Greek word meaning ‘dwarf’ or ‘extremely small’. The concept was first introduced 50 years ago when Physicist Richard Feynman delivered a talk in 1959 entitled "There is Plenty of Room at the

Bottom," in which he commented that there were no fundamental physical reasons why materials could not be fabricated by maneuvering individual atoms. In her book *Nano Materials in Architecture, Interior Architecture and Design* Sylvia Leydecker specifies that there is still not a clear and generally applicable definition on an international level for the term "nanotechnology" and she adds, "in most cases it serves as a general heading for all manner of analyses and material investigations at nano-scale." Generally, speaking nanotechnology therefore describes any activity magnitude of less than 100nm" (12). Smart nanocsale materials may be able to overcome the limitations of by other smart materials. Nanomaterials can be metals, ceramics, polymeric materials, or composite materials. Their defining characteristic is a very small feature size in the range of 1-100 nanometers (nm). At the nanomaterial level, some material properties are affected by the laws of atomic physics, rather than behaving as traditional bulk materials do. Nanotechnology offers the potential to build from the 'bottom up' creating materials with specific new properties such as self-cleaning property.

There are two different self-cleaning properties provided by nanotechnology, Lotus-Effect and photocatalysis. Leydecker emphasizes the misunderstanding of self-healing property and says "It is important to note that the term "self-cleaning" in this context is misleading and does not mean, as commonly assumed, that a surface need not to be cleaned at all" (72). This property however, generally contributes to facility management, in other words, provide low-maintenance.

Lotus-Effect is one of the best-known means of designing surfaces with nanomaterials. Leydecker mentions that the investigation of self-cleaning surfaces has been introduced in the 1970s by the biologist Wilhelm Barthlott. Barthlott examines a self-cleaning effect that can be observed in several plants such as oriental Lotus leaves, the European Nasturtium and the American Cabbage. The common feature of these plants is a “microscopically rough water-repellent (hydrophobic)” surface covered with tiny knobbles, which these knobbles provide little contact surface for water to settle on. In addition, the rough surface is strengthened by a layer of hydrophobic wax. The result of this combination is a super-hydrophobic and self-cleaning surface. Water that cannot hold the surface rolls off the leaf taking with it any dirt. Artificial “lotus surfaces” created with the help of nanotechnology; small quantities of water such as rainwater are enough to clean the surface. Without application of water, therefore this feature is ineffective. The application can be made by painted on an existing surface or covering with a composite material that coated[12] with Lotus-Effect surface. To sum up, Lotus-Effect reduces cleaning requirements



and surfaces that are regularly exposed to water remain clean (59-63)

**Figure 20, 21, 22** Lotus-Effect self-cleaning property (Leydecker 60)

[12] The coatings incorporating certain nanoparticles or nanolalyers have been developed for certain purpose. It is one of the major applications of nanotechnology in construction.

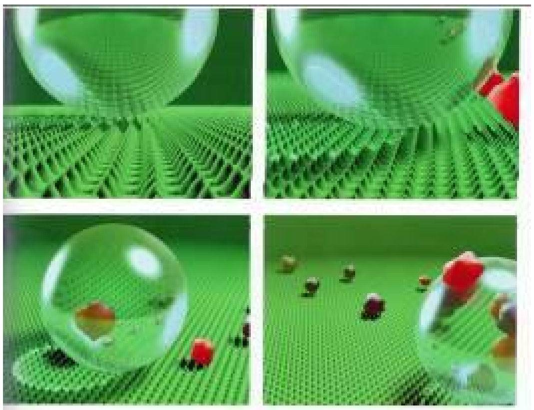


**Figure 23, 24, 25, 26** Visualization of process on Lotus-Effect self-cleaning surface (Leydecker 61)

Photocatalytic self-cleaning is the most widely used nanomaterial application. “It’s primarily effect is that it greatly reduces the extent of dirt adhesion to the surface” (72). For Photocatalytic self-cleaning has three requirements, ultra violet light, oxygen and air humidity. “Organic dirt on the surface of a material is decomposed with the help of a catalyst- usually titanium-dioxide (TiO2) The nanoscale dimension of TiO2 makes a highly reflective catalyst, spending up the decomposition process rapidly without being used up so the effect is lasting” (72). The discovery of TiO2 is carried out in 1908 and its photocatalytic property was discovered by Akira Fujishima at the University of Tokyo although it has the hydrophobic properties were discovered much later. In contrast, from the Lotus-Effect surfaces, photocatalytic surfaces are transparent and can be applied to glass with no effect on transparency. Basically, the process is the exposure of dirty glass to sun, initiating photocatalysis, and loosening the dirt and allowing water to spread and form a film washing away. Photocatalytic surfaces coatings are often applied to glass or ceramic façade panels with a vacuum coating technique or to membranes. It is suitable to be used with the combination of other type of functions such as solar-protection glass. Photocatalytic tiles have been on the market since 1994.

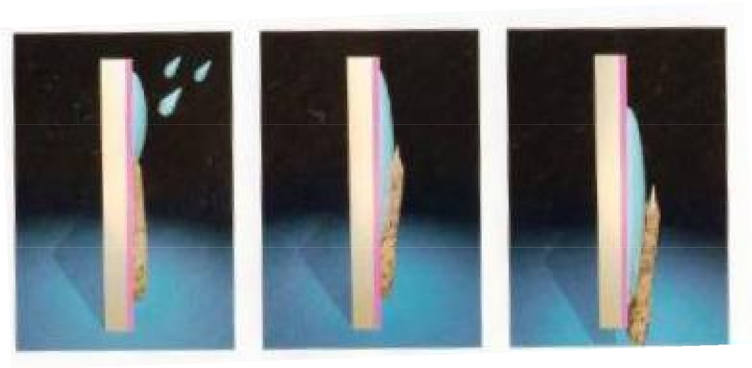


**Figure 27, 28, 29** Visualization of process on photocatalysis self-cleaning surface (Leydecker 76)

### 3.5. High Insulating Smart Materials

There are two specific and well-known smart materials, which exhibit high isolation performance, Aerogel, and a type of Teflon based material called ETFE (Ethylene Tetrafluoroethylene)

#### 3.5.1. Aerogel

Nanotechnology generates products with many unique characteristics and these materials can be used in many areas of design and construction. These characteristics can remedy current construction problems, and may change the requirement and organization of construction process. Nanostructured products include lighter and stronger structural composites, improving pipe-joining materials and techniques, increasing properties of cementitious materials, increasing the sound absorption of acoustic absorbers and as, mentioned in the previous chapter, providing low maintenance coating and also reducing the need for thermal insulation. One of these unique nanostructured materials, Aerogels, are highly porous solid materials with extremely low densities with large, open pores, and high specific surface areas. These results in unique physical properties, such as extremely low thermal conductivity and low sound velocity, combined with high optical transparency (Leydecker 128-9).

Aerogels are not recent products of modern technology. The first aerogels were prepared in 1931 by Samuel Stephen Kestler. However, it saw little development for several decades since the 1980's a great amount of research has been done on aerogel by scientists at NASA. They have developed and used aerogel to trap space dust particles aboard the Stardust13 spacecraft. The particles vaporize on impact with solids and pass through gases, but can be trapped in aerogels. NASA also used aerogel for thermal insulation of the Mars Rover and space suits. A new version of aerogel was recognized by Guinness World Records with for 15 distinctive properties, including best insulator and lowest density solid (Leydecker 128-9) and (Phalippou 80).

Although the name aerogel means air gel aerogel is made up of microscopic beads or strands connected to form a continuous network. Since the network fills space and supports itself, it is considered as solid.

[13] Stardust is the first U.S. space mission dedicated solely to the exploration of a comet, and the first robotic mission designed to return extraterrestrial material from outside the orbit of the Moon.

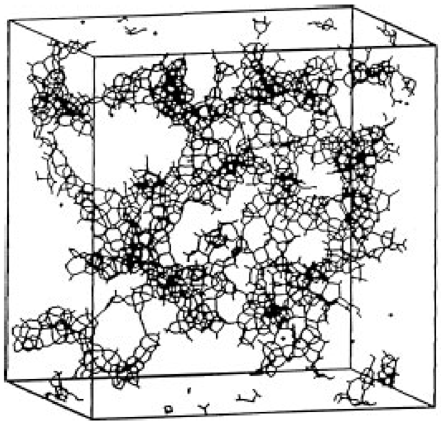
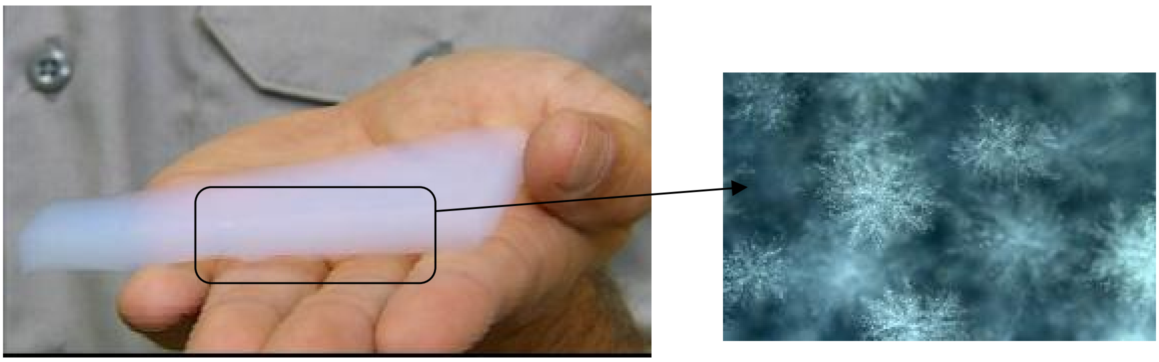


**Figure 30** Schematic structure of a silica aerogel (Uhlmann and Ulrich 45)

Commercially, aerogels have been used in granular form to add insulation to skylights. Transparent silica aerogel would be very suitable as a thermal insulation material for windows, significantly limiting thermal losses of buildings. Other commercial applications of aerogel include durable and flexible material, fibrous blankets, tennis racquets, thickening agents in some paints and cosmetics.



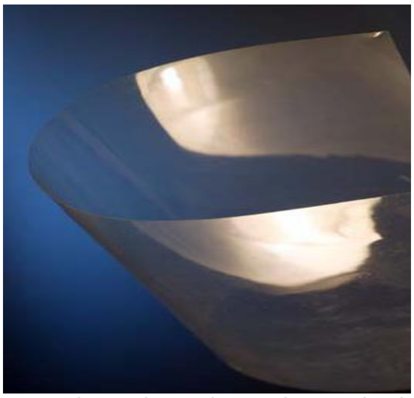
Discovery Channel (2007) Deconstruction: House of Future (24:12)

**Figure 31** Aerogel and its molecular structure

### 3.5.2. ETFE (Ethylene tetrafluoroethylene) Films

Varieties of plastics resistant to ultraviolet rays have been developed which have longer life spans, and better performance. ETFE (Ethylene tetrafluoroethylene) is a fluorocarbon-based polymer that belongs to group of plastics. ETFE like Aerogel is not a new material but only recently has started to be used commercially. First developed by Dr. Plunkett in 1938 at DuPont, it is one of the seven fluoropolymers generated from the invention of PTFE (polytetrafluoroethylene) or the plastic more commonly known as Teflon. ETFE was designed for high corrosion resistance and strength over a wide temperature range. In addition, it has a high melting temperature and emits no toxic fumes when ignited. ETFE is a thermo-plastic, which is usually used as a form of film. DuPont produces this EFTE films under the name of Tefzel. Many other manufacturers produce ETFE film under different names such as 3M's Dyneon and Nowofol's NOWOFLON **(**LeCuyer 8).

ETFE film is only 1% of weight of glass, transmits more light and in 24-70% less expensive to install. As with all fluoropolymers, ETFE has high and low temperature capabilities, great durability, low friction, very high electrical and chemical resistance and good thermal properties. It is also unique for its mechanical toughness, and its properties are very long-standing; it does not discolor or harden (Allen 2). ETFE is commonly used for tank construction, and packaging of food and pharmaceuticals. It has been used by NASA especially for wire insulation in the spacecraft and space stations. Regarding its properties, it has been also discovered by civil engineers and been used as construction material since the beginning of 2000s (LeCuyer 5).



(http://www.hightexworld.com/page/news.html; cited 28.12.2008)

**Figure 32** a sheet of ETFE film

These developments in material science change the understanding of the limits of materials as well as the perception of the products and their application. As mentioned throughout the chapter, these materials change their forms, generate energy using their surroundings, maintain themselves and provide new building solutions with a high comfort level. Through these properties, smart materials provide wide range of opportunities for designers. Although designers recently have met these materials, as the next chapter presents, they are excited to use them in their works.

## 4. SMART MATERIALS IN ARCHITECTURE

Smart materials are constantly emerging, evolving, and rapidly becoming part of architecture. The use of smart materials in architecture is a dynamic and innovative issue merging research and development and advances in material science offer great opportunities for innovations in architectural design and building technology. The ambition of architects provokes technological developments both in terms of design and in materials for construction. “The possible applications of smart materials in architecture are broad, ranging from imbedded sensors and actuators for control of the performance of structural systems, energy-generating systems, controlled mechanical systems, and innovative forms. The buildings of the future will utilize these new systems, and will change the architectural realm” (Zisko 13).

Opportunities are already extensive. As Addington and Schodek point out, current limitations of applicability of smart materials are depend on cost and availabilities, and note express that the introduction of smart materials into architecture happened through “highly visible showpieces” such as thermochromic chair backs and electrochromic toilet doors and later through attractive demonstration projects (1-6). An attempt to use smart materials in design is Juergen Mayer’s ‘heat’ chair, which uses thermochromic paint to show the outline of the person using it. Another example is the ‘hanabi’ lamp designed by Nendo group. "Hanabi" means “fireworks” whereas the literal translation from Japanese is “flower and fire.” The lamp is made of shape memory alloys so with the heat of the bulb the lamp opens whenever the light is turned on it closes when it is off.

(http://www.sfmoma.org/exhibitions/exhib_detail.asp?id=106-cited 22.03.2008)

**Figure 33** ‘Heat’ designed by Juergen Mayer (2002=

(http://www.nendo.jp/en-cited 25.05.2008)

**Figure 34, 35, 36** ‘Hanabi’ shape-memory alloy lamp by Nendo design (2006)

Smart materials are used in architecture generally for aesthetic rather than functional reasons, and smart materials, which change their appearance, are especially chosen as ‘show pieces.’ Most of the functional applications are theoretical in present. However, these are the early stage of the use of smart materials. Architects are experimenting with small-scale use of these materials. Larger applications will be realized after they gain more knowledge. The Cyclebowl is one of these visual applications of smart materials on an architectural scale. Designed by Atelier Bruckner and developed for Expo 2000 Hanover, the skin of Cyclebowl is made of three layers of ETFE. These layers have positive and negative prints. The middle layer is pushed against the other two layers creating a change in pattern on the façade of the building with a pneumatic control.

**Figure 37, 38** The change in pattern on the facade of Cyclebowl (Ritter 13)

Addington and Schodek criticize designers the ambitious enough to use these smart materials, but who neglect the technology that they are based on. For example, Addington and Schodek propose integrating smart materials into conventional buildings, such as covering buildings with smart gel, or smart rooms that react individually to each user according to their needs. Contrast to this limited use, they note that “[m]any architects further imagine building surfaces, walls and facades composed entirely of smart materials” (4). Addington and Schodek specify two problematic aspects, caused by this neglect. Firstly, designers consider that these new materials and technologies perfectly fit with their “normative practice.” Addington and Schodek explain this as “making design simpler as the manifestation of inventions could shift from the responsibility of the designer to the material itself” (iv). As to this idea, designer use the materials is capability, rather than designing they only name it. Secondly, by neglecting the actual technologies behind the new materials, designers miss many opportunities and radical new approaches.

In Addition to this critique, Addington and Schodek mention the great distance between engineers and scientists who invent and develop these new materials and technologies, and architects and designers who consider that merely a pragmatic, rather than technological knowledge of materials is needed. For an architect or a designer who intents to use new materials and technologies, the primary subject is to understand the basic principles and the use of these materials as they use conventional ones to create new design elements (viii). This critique is crucial for the thesis, which aims to encourage architects and designers to use smart materials more consciously, to benefit from smart materials more extensively and to find new design solutions that provide not only convenience but also sustainability. Despite these problems, as the use of these materials increases, in the near future architects and designers will be more willing to use these materials in theories and applications, which are efficient and beneficial. Smart materials will be used more in architecture including sustainable applications as demonstrated in this study.

### 4.1. Application of Smart Materials in Sustainable Architecture

Sustainable architecture, including several selected criteria for sustainability has been introduced in the second chapter. These criteria have helped to determine the group of smart materials introduced in the Chapter 3. This chapter includes the examination of each of these materials and their architectural applications according to the determined sustainability criteria. Related examination is conducted in the light of architectural examples. While some of these examples are already realized, most are still theoretical, however, they represent new and radical approaches to architecture. It is necessary to reemphasize that, rather than dealing directly with the sustainability of each smart material, this study analyzes the properties of these materials that support sustainability. The table below summarizes this study's propositions for areas in which smart materials can be used to support sustainability in architecture. Each item in this table will be studied in detail in Chapter 4.

Architecture uses materials to compose the built environment. As Le Corbusier states, "Architecture displays itself through the surface and the mass" (48). While composing the environment architecture forms surfaces. Contrary to the common thought that architects design spaces, Addington and Schodek agree with Le Corbusier and they state that "architects make (draw) surfaces" ( Addington and Schodek 5). The largest surface of a structure that an architect designs is the facade. Similarly, Le Corbusier states the relationship between the building envelope and its accommodation of function; "one day we noticed that the house, like the motor car, could be a simple external covering or membrane, containing multiple organs in free arrangement" (Von Moos 85).

The application of smart materials to the facade of a building has potential to strengthen the sustainability of the building by creating surfaces that can change,, which enables the control natural light and ventilation, as well as active surfaces generating electricity for the building, self-healing and self-cleaning surfaces which facilitate the maintenance of the building, and translucent surfaces with high isolation properties.

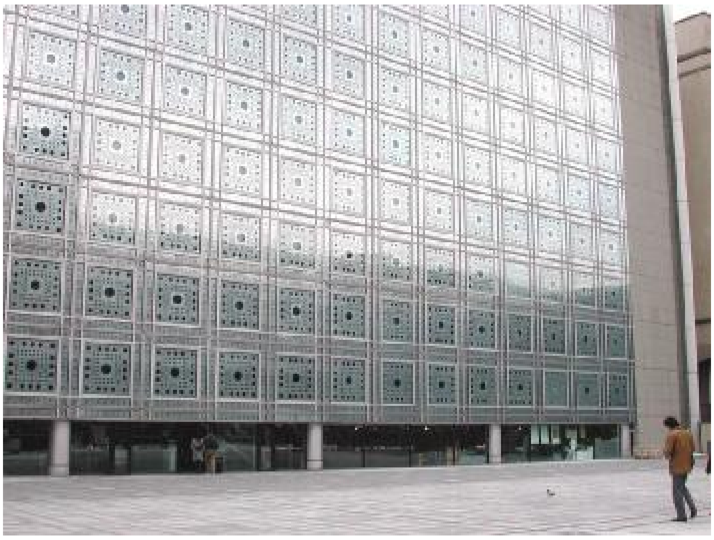
| PROPERTY | ECOLOGICAL USE / MATERIAL | MATERIAL | Ventilation | Control of Natural Light | Energy Generation | Temperature Control | Maintenance | Insulation |
|---|---|---|---|---|---|---|---|---|
| **Shape Changing Property** | Thermostrictive Smart Materials | Shape Memory Alloys | × | × | | × | | |
| | | Shape Memory Polymers | | | | | | |
| | Electrostrictive Smart Materials | Electroactive Polymers | × | × | | × | | |
| **Energy Generating Property** | Energy Exchanging Smart Materials | Photovoltaic | | | × | | | |
| | Electricity Generating Smart Materials | Piezoelectric | | | × | | | |
| **Self Maintaining Property** | Self Healing Smart Materials | | | | | | × | |
| | Self Cleaning Smart Materials | | | | | | × | |
| **High Insulation Property** | Aerogel | | | | | | | × |
| | ETFE | | | | | | | × |

**Table 5** Application of smart materials in sustainable architecture

### 4.2. Application of Shape Changing Smart Materials

Addington and Schodek define the surface as ‘an envelope [that] behaves like a boundary” (6). With the introduction of smart materials into architecture, these boundaries, which are physically limited by the material surface, transform into a “zone in which change occurs” (Addington and Schodek 6). One noticeable example of changeable zone facades is the Arab World Institute Building in Paris, designed in 1987 by architect Jean Nouvel who designed an interacting facade system that responds to outdoor light conditions thus he enables the building adapt to the surrounding. Although the interacting facade system does not actually use a smart material, it functions through a smart system. In doing so, it designates a good example for the new understanding of facades, and the integration of technology and architecture. Similarly, in *Towards a New Architecture*, Le Corbusier defines the surface of a building as a functional skin. This functional and structural skin covers the space to define the form of the interior and to form a closed space; it also defines the internal conditions of this space (38).

The huge south-facing garden courtyard wall is designed as a 60-meter changeable facade of metal sunscreens with active sun control diaphragms. This device is made up of numerous and variously dimensioned metallic diaphragms set in pierced metal borders. These diaphragms operate like a camera lens to control the sun's penetration to the interior of the building. While externally, a subtle density pattern can be observed, the changes to the irises are dramatically revealed internally (Von Moos 86). With its complex mechanism integrated into its facade, the building recalls the famous saying of Le Corbusier: “A house is a machine for living in” (40).



(http://www.jeannouvel.fr/; cited 10.01.2009)

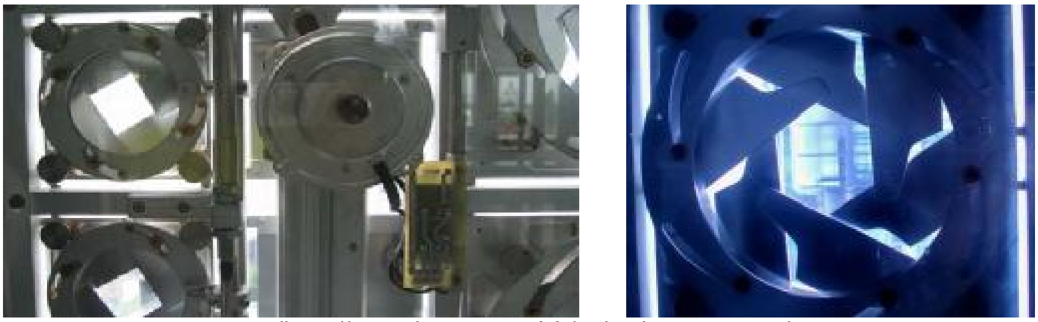
**Figure 39** the exterior view of the changeable facade of Arab World Institute (1987)

(http://www.jeannouvel.fr/; cited 10.01.2009)

**Figure 40** the interior view of the changeable facade of Arab World Institute

(http://www.jeannouvel.fr/; cited 10.01.2009)

**Figure 41** the metallic diaphragms of the South facade of Arab World Institute.



(http://www.jeannouvel.fr/; cited 10.01.2009)

**Figure 42, 43** the mechanism of the South facade of Arab World Institute.

Unlike Arab World Institute in which smartness is achieved using a mechanical system, the "Aegis Hyposurface" Project has a high-technological smart system. Aegis Hyposurface, designed by Mark Goulthorpe in 2002, is an active architectural surface made up of small metal plates. These metal plates are controlled pneumatically and they react in real time to electronic stimuli that they get from the environment such as movement, sound and light. Goulthorpe has developed the fundamental idea of this interactive surface with a large multi-disciplinary team of architects, engineers, mathematicians and computer programmers. Creating a facetted metallic surface that has potential physically modify itself in response to electronic stimuli from the environment. Driven by a bed of 896 pneumatic pistons, the dynamic 'terrains' are generated as real-time calculations (Kronenburg 214). In *Transmaterial 2,* Browenell believes that “Aegis Hyposurface marks the transition from autoplastic (determinate) to alloplastic (interactive, indeterminate) space, a new species of reciprocal architecture” (53). The Aegis Hyposurface effectively links information systems with physical form to produce dynamically variable, tactile ‘informatics’ surfaces.

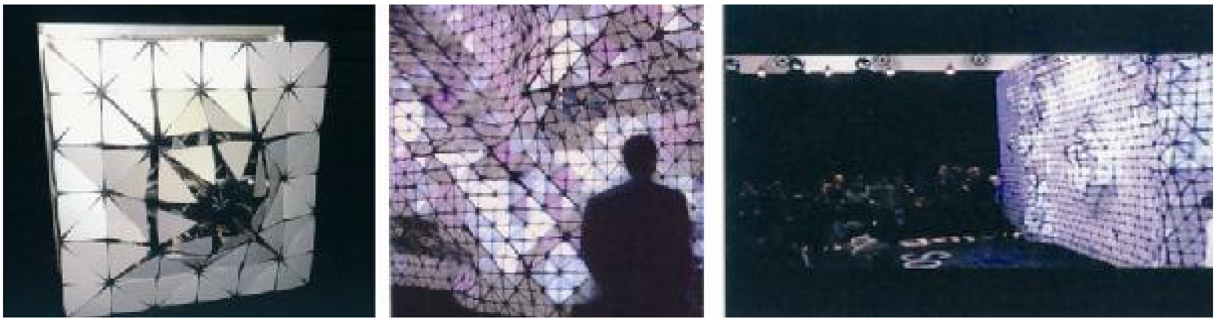


**Figure 44, 45, 46** “Aegis Hyposurface” by Mark Goulthorpe (2002) (Addington and Schodek 224)

Shape changing materials can construct similar changeable and interacting facades without complex mechanisms in other words ‘machines’ or digital mediums like Aegis Hyposurface is using. As these materials find their place in the automotive industry and civil engineering[14] there are various ways that they can be used in architecture (Ritter 64). One application areas is facades of control of natural light transmission and air circulation inside the building. Several projects are designed with this

[14] Ritter gives an example of theoretical projects. “In Italy, a bridge has been built passive struts made from shape memory alloys with pseudoelastic properties. The shape memory alloy members are intended to attenuate any seismically induced forces in the structure” (Ritter 64).

understanding. Some use shape memory alloys and shape memory polymers while the others use electroactive polymers.

The project called interactive ‘Living Glass’ regulates air quality. Designed by architects Soo-in Yang and David Benjamin. It is still in the development phase. Living Glass is based on a premise that architectural elements could move in response to their environments. With minor changes, the system could be tuned for environmental control. By monitoring $CO^2$ levels in the air, Living Glass opens or closes its “gills” in response. It controls the air quality in the room by a thin, transparent film surface that automatically reacts through wires made of shape memory alloy. When, the $CO^2$ inside the room balances with the concentration outside, the gills close. This project uses material actuators rather than mechanical ones (Browenell 139). The Living Glass is a concept that imitates the idea of buildings behaving similar to the natural organisms around them.

(http://www.thelivingnewyork.com/lg.htm; cited 10.01.2009)

**Figure 47, 48** Full-scale demonstration of the ‘Living Glass’

With this change, the facade of the building transforms into a responsive what is used as a transporter for collecting and channeling air and light. By increasing the contact between the building and its environment, this responsive skin similar to human skin provides sustainable control of natural ventilation and light. As it is mentioned in the Chapter 2, the ventilation and lighting systems consume the larger amount of energy. This application of shape changing smart material on facades provides a radical control of natural ventilation and natural lighting without any energy consumption or with a little amount.

The application of smart materials makes a building a part of its surroundings. Through the property of changing the formal appearance, the application of shape changing smart materials on facades strengths the connection between a building and the environment. This application lets air and light flow through the building and the building become a part of its environment like a living organism.

### 4.3. Application of Energy Generating Smart Materials

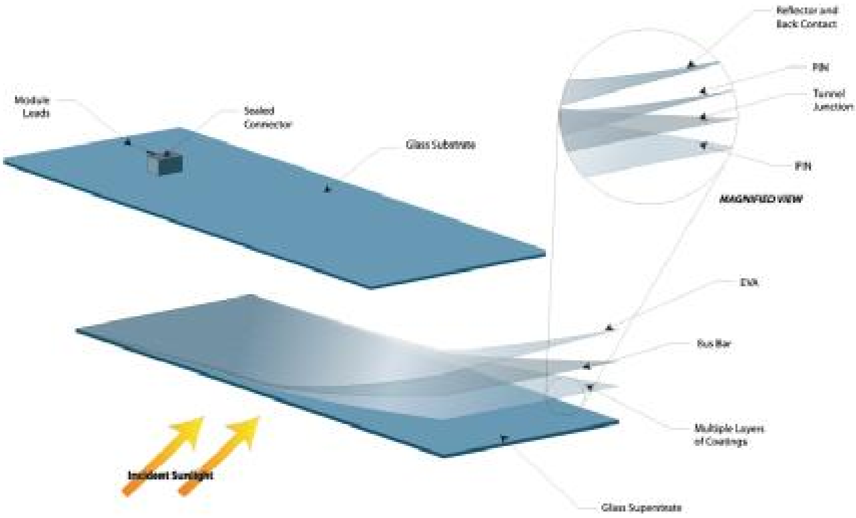
The worldwide energy shortage has caused improvement of new systems that provide sustainable energy sources. Gürsoy describes, “[d]evelopment as being not the consumption of unlimited energy, but it is the production of energy from suitable resources with suitable technologies and to use this energy efficiently with a little loss” (30). As mentioned in the previous, chapter generating energy is one of the main concepts in sustainable architecture. As commonly known, sustainable energy sources are the wind and sun. The architectural application of these new systems generating electricity from these sources is a wide field. This section covers the application of smart materials contributing to energy generation using these systems. Two different methods of energy generation through smart material are considered in this chapter: the use of solar powered energy-exchanging smart materials and materials using wind power to generate energy. Both applications propose to use facade of the structure for these applications.

### 4.3.1. Application of Energy Exchanging Smart Materials

As introduced in the previous chapter photovoltaics have been used in solar panels to convert solar energy into electricity about two decades ago by NASA. Since 1977, United States Department of Energy has been encouraging the use of solar energy, launching the “Million Solar Roof” Initiative. This attempt increased both the use of solar panels and their improvements. In consequence, the term ‘building-integrated photovoltaics’ has became a new term in architectural vocabulary. The new generations of photovoltaics are much more efficient than the old ones. They have also wider application methods and areas such as the thin, translucent photovoltaics film, and this area is developing rapidly. The latest example is ‘solar powered glass’ which is developed by company named ‘xsunx’, which produces solar modules. ‘Solar powered glass’ is an innovative solar technology that allows glass windows to produce electricity from the power of the sun. This technology enables architects to apply a transparent and photovoltaic glazing to glass and other transparent substrates.[15]

Besides classical application methods and designs, architects seek new approaches to the use of photovoltaics in a building. A good example of this is “SmartWarp,” a

[15] http://www.xsunx.com/pdf/SpecSheetOctober28-2008.pdf




(http://www.xsunx.com; cited 10.01.2009)

**Figure 49** Schematization of 'solar powered glass.'

concept for a new building material that integrates the segregated functions of a conventional wall, such as shelter and insulation, and compresses them into a single composite film that can be erected in a fraction of standard building time. SmartWrap is simply the building envelope of the future: a composite that integrates the currently segregated functions of a conventional wall and combines them into a single advanced composite. Ritter emphasizes the symbolic importance that SmartWrap represents and he says; "SmartWarp is the name of an innovative, polyvalent building skin which, on the basis of a newly developed transfer technology, it is expected to open up new possibilities for the industrial and cost-efficient use of smart materials in the future" (Ritter 140). SmartWrap is designed by Stephen Kieran and James Timberlake and is an outcome of a research conducted with graduate students at the University of Pennsylvania. The prototype has been installed for the

August 2003 SOLOS exhibition at the Cooper Hewitt National Design Museum in order to demonstrate its components and technology (Kronenburg 228-31).

**Figure 50, 51** Exterior view at night and interior view of SmartWrap (2003) (Ritter 140-41)

By using different kind of technologies in a single material, SmartWrap insulates, stores energy, and digitally regulates temperature, as well as providing and controlling light and it enables users to program different panels to light up, display an image, or switch from transparent to opaque as needed. The printable skin is made up of a substrate, an applied or imbedded layer, and four printed layers. The recommended substrate, a polyester mixture, polyethyleneapthalate (PET) is colorless, and fully transparent. Organic light - emitting diodes are attached to the surface and they function as a type of monitors[16].

[16] http://www.kierantimberlake.com/research/smartwrap_research_1.html

The four smart layers act independently, using different technologies,

- Organic light-emitting diodes (OLEDs) add self-illuminating ability to the structure eliminate need for lighting and enable to change the internal and external appearance to change,
- An Organic Thin Film Transistor controls circuitry or 'brain' of SmartWrap,
- Microcapsules of Phase Change Material (PCM's)[17] regulate thermal conditions,
- An Organic Solar Cell (OPV's) provides sustainable and inexpensive power for the walls and for the whole building or other application.

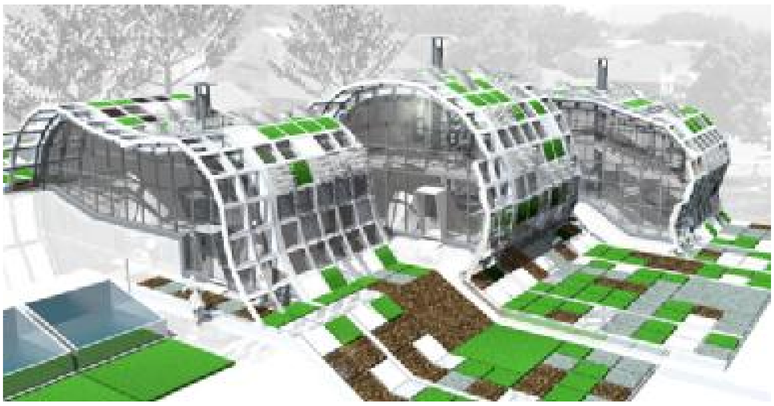
SmartWrap is lightweight, can be transported and installed very quickly; it is also infinitely reusable (Ritter 140-41).

### 4.3.2. Application of Electricity Generating Smart Materials

Other than energy exchanging materials, there are electricity-generating materials such as piezoelectric materials, which can also be used to be integrated to the facade of a structure to generate energy. This technology is different from energy exchanging materials in terms of inputs and outputs. As it is mentioned in the previous chapter, piezoelectric materials are able to transform mechanical energy to electricity. It is proposed that wind is used as the energy source in the application of piezoelectric materials on facades. When wind creates pressure on the facade,

[17]"There are three phases of matter that we are most familiar with: solid, liquid and gas. When a substance reaches a certain temperature, it changes phase. However, for a substance to undergo this change, energy such as heat must be exchanged. When an object goes from liquid to solid, heat is released, and when it goes from solid to liquid, heat is absorbed. This is the principle behind phase change materials as temperature regulators: When an environment gets hot, the heat is absorbed to later be released when it is cold" (http://www. kierantimberlake.com/ research/smartwrap_ research_1.html).

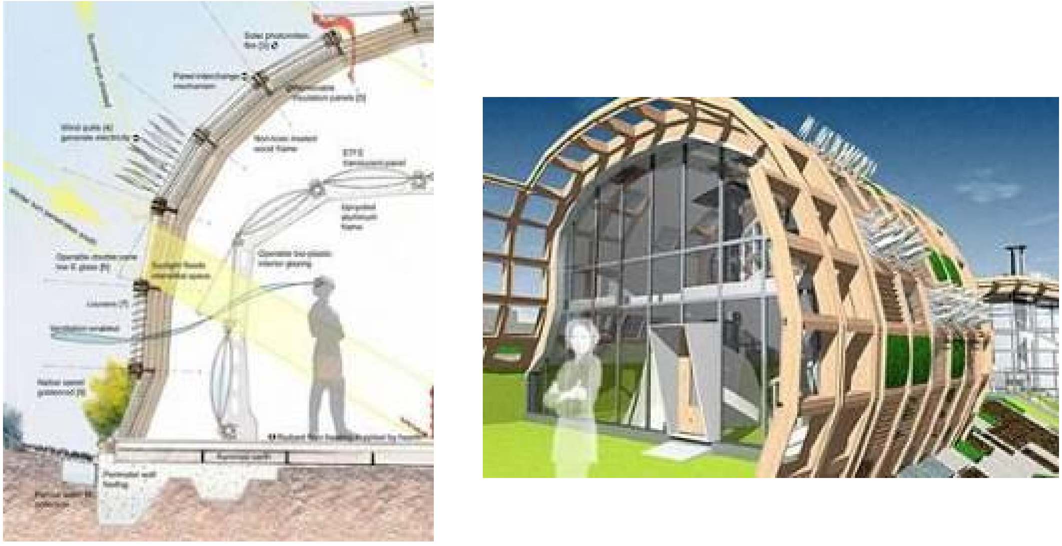
piezoelectrics produces electricity that is able to power any type of appliance. Piezoelectric materials can be also used in areas other than facades. As they generate electricity through a pressure, they can be applied to floors or other surfaces experiencing continuous movement. Although their applications are more limited compared to photovoltaics, they have potential. At present, there is no project known to employ wide-ranging piezoelectric materials, however a project known as MATscape is employing these materials in to the façade of structures.



(http://www.archinode.com/c2c.html; cited 10.01.2009)

**Figure 52** Housing units and contiguous landscape elements covered with MATscape (2005)

MATscape a project designed by Mitchell Joachim proposes an innovative example of green design of a skin, in the form of a grid. This grid skin is made out of various blocks assembled to cover the structure underneath. It reacts not to a single environmental input, but several, including solar energy, wind, rain and ambient temperature, using a variety of technologies in each component of the grid according to user's needs and environmental conditions of the site. This grid skin also produces energy by using either solar panels or the units called wind quills, which are filled with piezoelectric materials.



(http://www.archinode.com/c2c.html; cited 10.01.2009)

**Figure 53, 54** the wall section and the exterior view of one of the MATscape buildings

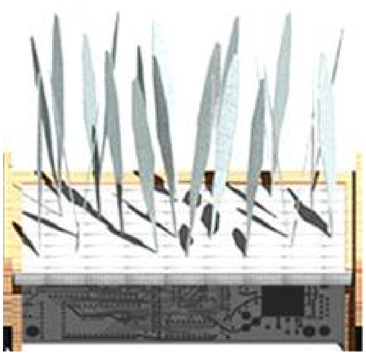


**Figure 55** wind quills with piezoelectric cells (Ritter 142)

Even with energy conservation, energy consumed is significant, and the source of this energy has an important effect on ecology. Sunlight and wind provides clean energy sources; however, the application of these sources in conventional buildings needs fragile and complicated structures and systems such as solar panels and wind tribunes. In some cases, they are added to the building after the design or the construction whereas the thin transparent photovoltaic films and piezoelectric materials provide an innovative solution that enable architects to integrate these new energy generating materials in their designs easily.

Besides the shape changing materials, energy generating smart materials makes the building to connect with its surrounding. These materials provide building to use the natural energy sources. In one sense building similar to a plant obtain its own sustainable energy and become almost independent from the energy infrastructure.

### 4.4. Application of Self Maintaining Smart Materials

The application of self-healing coating could infect reduce cost caused by the repair which includes not only the material but also the energy loss which occurs during the repair process, such as labor, installation and equipments. Except engineering applications, at present there is no example of an architectural project that employs applications of self-healing smart materials. However, as a new and experimental technology, it is expected to start attracting architects' attention in the near future. Kesler's saying demonstrates the applicability of self-healing materials to any area, stating, "The broad and interdisciplinary environment towards which this field is developing gives an outstanding opportunity for multidisciplinary inspiration and collaboration. This expansive scope is well reflected by the topics that are selected as the focal points of this international effort on research in self-healing materials such as asphaltic materials cementitious materials, composites and hybrids, metals, paints and other coatings" (Kesler 481).

Self-cleaning smart materials have a greater potential for use than self-healing materials. For that reason, there are a number of buildings where self-cleaning materials have already been used (Browenell 140). One of these applications is the Ara Pacis Museum located in the historic center of Rome. The Museum is designed by Richard Meier.

**Figure 56** Ara Pacis Museum (2006) (Leydecker 65)

The building is characterized by a large block of travertine, which connects the building with its historical surrounding, and its white surfaces as a typical of the language of Meier connect the building with the contemporary. The application of a lotus effect coating integrated invisibly into the white surfaces ensures the durability of this design concept. Another example is a commercial building in Croatia, which is designed by architect Andrija Rusan. As with the Ara Pacis Museum, its white facade is part of its design concept. It’s monolithic cubic form and into which windows are carved makes the building look like a crystal. The lotus effect facade coating provides sustainable, long-term protection, without needing any to be renewed for a long time (Leydecker 64-6).

**Figure 57, 58, 59** Commercial Building Designed by Andrija Rusan (2006) (Leydecker 66)

Both applications of Lotus effect coating provides architects freedom to demonstrate their designs without being limited by concern of maintenance costs. Besides, the Lotus Effect coatings on facades of the buildings photocatalysis surfaces further strengthens this freedom. Roof tiles that have self-cleaning photocatalysis effect are good examples of a material application of this technology in architecture. The roof tiles have been launched on the market in 1994 by a Japanese tile producer, and since then their use has increased in Japan as well as in various other countries. As mentioned before the photocatalysis effect can be applied to various materials such as glass, ceramic and membranes. Because it can be applied directly onto other materials, it has many possible uses. There are many examples of effective use of photocatalysis effect, two outstand ones are mentioned here Muhammad Ali Center and The Hyatt Regency Garden Chapel. The Muhammad Ali Center located in Louisville and designed by Beyer Blinder Belle Architects has a facade covered with ceramic tiles with photocatalysis effect. The ceramic tiles with different colors arranged on 30 cm X 60 cm grid create a mosaic montage of Muhammad Ali in action fighting positions and facial close-ups. “To maintain a consistently good appearance and to keep down the cost of cleaning the tiles are equipped with a photocatalytic self cleaning surface coating. The coating is baked onto the glaze of the tiles and is therefore immediately durable. In addition, the surface is also air purifying, breaking down pollution and exhaust gases from vehicles and industry in the surrounding atmosphere. Investigations have shown that 1.000 m2 of photocatalytic facade has the equivalent effect of 70 medium sized deciduous trees" (Leydecker 78).

**Figure 60** Muhammad Ali Center designed by Beyer Blinder Belle Architects (2005) (Leydecker 78)

The Hyatt Regency Garden Chapel designed by Obayashi Corporation is an example of membrane structure with a built-in photocatalytic effect. The chapel located in the garden of the Hyatt Regency in Osaka, is a structure covered with white membrane relevant to its function. "Without its photocatalytic self-cleaning surface, the white of the membrane would have not lasted long without having to be cleaned regularly or even replaced at intervals" (Leydecker 80).

**Figure 61** Hyatt Regency Garden Chapel constructed (2001) (Leydecker 80)

In the second chapter, it is mentioned about Life Cycle Assessment. Briefly, Life Cycle Assessment is a process that investigates the impact of a product at every stage in its life, from preliminary development through obsolescence. Life stages include also use and maintenance of the material. Maintenance is one of the biggest costs for a building. These outgoings cover the cleanup and the reparation of the surfaces and components and can easily exceed the original construction costs. This includes the cost of labor, cleaning materials, equipment, and the replacement of items. “Less frequent cleaning of materials reduces the exposure of the building occupants and janitorial staff to cleaning chemicals this is especially important for surfaces or systems that must be cleaned with petroleum-based solvents” (Kim 20). Self-maintaining smart materials have significant potential as part of the solution for this problem.

### 4.5. Application of High Insulation Smart Materials

There are several key issues in sustainable architecture, one of which is the thermal insulation. Proper insulation could reduce energy consumption and building operating costs by preventing both heat gain and loss. Limiting such heat transfer reduces the building's heating and cooling loads and thus its energy consumption. Windows and skylights allow daylight to reach the interiors of buildings, reducing the need for artificial light, so increasing the use of natural light will lead to conserving electrical lighting energy, shaving peak electric loads and reducing cooling energy consumptions. However, windows are the weakest point in the building envelope in terms of energy loss, and much research has gone into developing more efficient window systems. The previous chapter has given brief information on selected high insulation smart materials aerogel and ETFE (Ethylene tetrafluoroethylene). In this section, their use in architecture will be examined through examples of architectural projects.

County Zoo in Milwaukee and a school extension building in London are outstanding examples the application of aerogel in architecture. The Florence Mile Borchert Big Cat County building is designed by the Zimmerman Design Group. The building is constructed of stone, concrete and a large surface of aerogel applied glass roof to provide a more natural environment for the big cats. The material added to the glass roof of the zoo, contributes to greeter energy efficiency. It provides not only diffuse, glare-free natural daylight but also thermal insulation. By the help of this material, the glass roof of the zoo provides greater energy efficiency.

**Figure 62, 63** Glass roof of The Florence Mile Borchert Big Cat County building (2005) (Leydecker 132)

A School extension building in London uses aerogel filled glass panels in a different way. Unlike the County Zoo building, the panels are used vertically on the facades. The south facade of the building gets most day lighting therefore, to benefit from the daylight without creating a greenhouse effect, panels are used on the entire south facade. The panels soften the daylight and provide excellent thermal insulation[18]. The result is reduced energy cost (Browenell 14, Leydecker 132-33 and Pfundstein 20).

**Figure 64, 65** Aerogel filled panel surface in school extension building in London (2005) (Leydecker 133)

18 Insulation property for aerogel is five times better than traditional foam (Browenell 14)

ETFE provides a flexible, lightweight, and durable alternative material for designers. In architecture, ETFE are used in the form of pillow that creates high insulation. These pillows consist of three or four layers of ETFE into which air is pumped continuously by a solar-powered heating system. Once inflated the pillows provide a higher degree of insulation than glass.

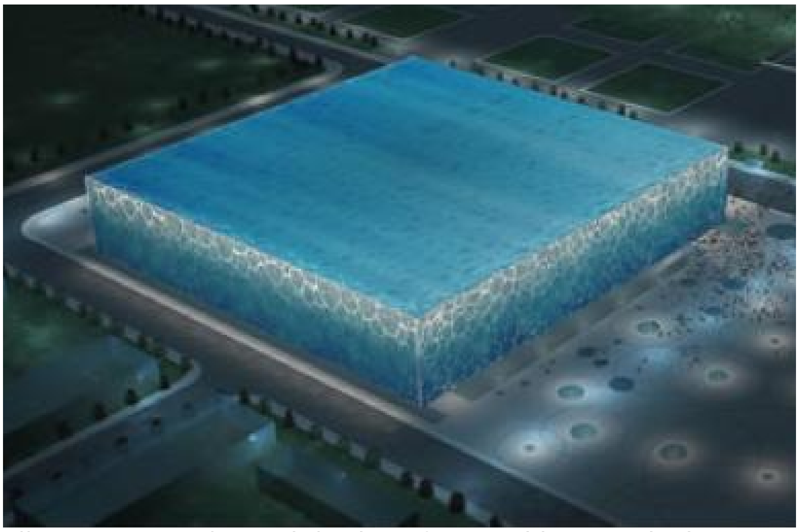
ETFE is used on a large scale in architecture as a building skin with the Eden Project in 2001. The Eden project consists of two biome[19] structures located in United Kingdom. The project is designed by designer Tim Smit, architect Nicholas Grimshaw and engineer Anthony Hunt. The Eden Project aims to recreate the world's biodiversity in an elaborate geodesic dome structure. Over 30.000 m2, the project comprises of eight geodesic domes forming two biomes for trees and plants. There is also an outdoor biome, a visitor centre, an outdoor amphitheatre and an access road (Robinson-Gayle 324).

(http://www.edenproject.com/; cited 15.01.2009)

**Figure 66** Eden Project (2001)

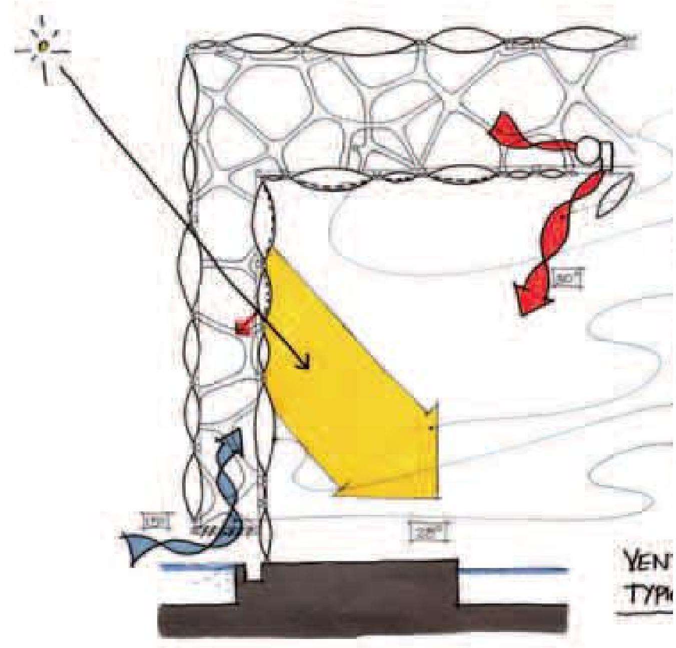
[19] "A biome is a climatically and geographically defined area of ecologically similar climatic conditions such as communities of plants, animals, and soil organisms" (Campbell 10).

The Allianz-Arena, the Beijing National Stadium and the Beijing National Aquatics Center are examples of other structures covered entirely with ETFE. The latest application of ETFE is The National Swimming Center, also called the "Water Cube," which is one of the symbolic buildings of 2008 Beijing Olympic Games and located inside the Olympic Park. The project has been co-designed by China State Construction and Engineering Corporation, PTW Architects and ARUP from Australia The main structure adopts a tensile space polyhedron steel frame structure. The different, blue ETFE pillows is filled with air, arranged in the wall and roofing. In addition to the ETFE pillows, in order to strengthen increase the thermal insulation architects have designed the exterior envelop with two layers thus, creating an air pocket, which acts as a natural ventilation system.



(http://www.arup.com/eastasia/project.cfm?pageid=1250; cited 15.01.2009)

**Figure 67** The National Swimming Center in Beijing constructed (2008)




(http://www.arup.com/eastasia/project.cfm?pageid=1250; cited 15.01.2009)

**Figure 68** Air pocket between the ETFE pillows of The National Swimming Center building

There is a lack of analysis data related to architectural applications for most of the smart materials, however as aerogel and ETFE have extensive use in architecture, more data for these materials exist. Aerogels are highly porous solid materials with extremely low densities. Because of porosity and nanometer pore size, silica aerogels are highly insulating materials with thermal conductivity lower than still air. Aerogels have the lowest thermal conductivities of all solids. Therefore, they have the highest potential for applications for insulation the architecture and are among the most effective thermal insulation materials. Additional advantages are a lack of flammability and transparency (Bindra 86 and Couillard 23).

As ETFE is one of the most stable organic combinations, resistance to all environmental influences is very high. Brunel University in Middlesex and Buro Happold Consulting Engineers in London conducted a study of the environmental effects of ETFE manufacture and use for building cladding. The study compares ETFE foil cushions to 6 mm glass and concluded the following about the sustainability of ETFE for use. “ETFE foils can improve the environmental performance of a building from two points of view; there is the opportunity to reduce the overall environmental burden incurred by the construction process itself; and there is also the opportunity to reduce the burden of the building during its lifetime (Robinson-Gayle, Kolokotroni, Cripps and Tanno 325). ETFE foil pillows exhibit better insulation than triple glazed glass due to the air trapped between layers and insulation provided can be improved by adding more ETFE layers. In addition to insulation, ETFE reduces the environmental burden through low maintenance requirements, 100% recyclability and a life expectancy that is far beyond 20 years.

The application of shape changing, energy generating, self-maintaining and high insulation smart materials in different aspects make the building to be a part of its surrounding and to closer one step to be independent. These materials provide the minimization of the energy use for ventilation and lighting, generation of energy from natural sources, reduction of maintenance cost and energy lost. These gained properties contribute the sustainability of the building in the literal sense.

## 5. CONCLUSION

The best way to predict the future is to design it.

Buckminster Fuller (124)

Today's sustainable buildings depend on conventional products and materials, existing methods of analysis and design tools. The next generation of sustainable buildings will have to be radically different from today's versions, and will be designed using new materials and approaches that are expressed in this study. Smart materials are one of the key components of these new approaches. These are new materials are in integration with the environment, produce renewable energies, maintain themselves, minimize energy consumption and maximizes use of natural light usage. Because of the present lack of data, the research and development needed to test these material properties under a variety of conditions cannot begin soon enough.

The journey to towards ultimate sustainable buildings is a long and difficult process. However, there is a start on this difficult path and the basic concepts needed to achieve sustainability in the built environment are understood by architects. In his paper, "The Challenge: Proposals for Strategies and Targets towards Sustainable Building," Peter Schmid emphasizes the current problems and issues of ecological design. He mentions the perception that this is the only planet humankind has, there is simply no other. The outcome is that significant reductions in consumption have to be considered to survive and begin the process of long term planning. The built environment contributes to a large extent to the factors that create global environmental problems in terms of waste, material and energy use and gas emissions. Today, sustainable building and construction is seen as the vital elements of the much larger concept of sustainable development that aims environmental protection. Thus, sustainable design, as it has developed over the last decade, has reinvented old ideas and produced some new ones. Albert Einstein declared "[w]e shall require a substantially new manner of thinking if humankind is to survive" (Davidson 12). In the line with Einstein, in recent literature on sustainable architecture similar to Einstein, architects have called for a fundamental change in world views among design professionals. For example, in *Hybrid Architecture* architect Graham Farmer and sociologist Simon Guy suggest "[t]he challenge is to change the perceptions, attitudes, opinions, and motivations of designers" (27).

Technological improvements, especially enables by nanotechnology, provide new materials with special properties. These materials have been used in different areas such as the textile industry and medicine as well as architecture. The contribution of these new materials to architecture provides the opportunity of designing smart buildings with lightweight structures and new building elements that react to environmental conditions. The interaction with the environment leads also to the following question: Can this material property be used to support the sustainability of the building? In addition, the increase of the interaction with the environment could make buildings more compatible. This compatibility could support ecologically sustainable environments. This is the central theme of this study.

In order to examine this idea, a theoretical research on sustainable architecture is conducted. A research, which has taken the form of selection criteria for smart materials, is also done in the third chapter. Smart materials are divided into four groups. These groups have been composed out of a wide range of smart materials, with an intense research, according to their application areas in a building. Chapter 4 is the documentation of the analysis that has been conducted according to these studies.

As mentioned in the second chapter, materials in sustainable architecture should pursue several criteria. These are use of recycled materials, minimal maintenance and long lifespan, easy installation and avoidance of toxins during production and utilization. In addition to these criteria, some important concepts like embodied energy and life cycle assessment are given to provide a clear understanding. As mentioned earlier, embodied energy is the energy required to extract, process, package, transport, install, and recycle or dispose materials that make up the building and life cycle assessment. Kibert describes it as “a method for determining the environmental and resource impacts of a material, a product, or even a whole building over its entire life” (30).

It is important to emphasize that rather than analyzing the sustainability of smart materials themselves, the properties of materials that support sustainability have been examined in this study. Therefore, the criteria to choose materials in sustainable architecture it can not be a measure of value. As mentioned in the fourth chapter, an in-depth analysis will be possible related with sustainability of these materials only when more data are available about their properties.

The most embodied energy of a building is contained in the materials. It includes the energy of the fuel used to power the harvesting or mining equipment, the processing equipment, and the transportation devices that move raw material to a processing facility. In this sense, the embodied energy of the smart materials is high. Materials with higher embodied energy usually have higher environmental impacts so, generally, the smart materials cannot be classified as sustainable materials. On the other hand, the embodied energy of a material also includes the degree to which contributes to overall sustainability. In addition to this, the life cycle assessment examines all material selection decisions including interpretation of the impacts such as the operational energy of a building. The life cycle of a building can be categorized into three phases: pre-building, building and post-building.

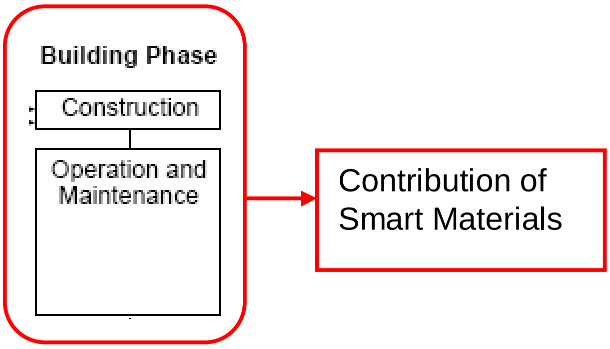



**Table 6** The integration of smart materials in Life Cycle Assessment phases

If smart materials are analyzed in this context, their contribution to sustainability can be mentioned in the building phase. As described in the fourth chapter, properties such as high isolation, self-healing, self-cleaning, energy generating and shape changing can contribute sustainability during the building phase. As mentioned before, a detailed assessment of the efficiency of these materials, and their contribution to sustainability is only possible with more data related with their architectural use. While some materials are being experimented, others have come into use recently. Increasing use of these materials in future architectural projects is expected to produce further data.

The ability of reacting to environmental conditions is the most important feature that strengthens the contribution of smart materials to sustainable architecture. Thereby the application of these materials on facades gives an opportunity to buildings to be in interaction with their surroundings. This opportunity brings together not only the ability of adaptation but also provides buildings to benefit from environmental conditions for different purposes such as generating energy, natural ventilation and lighting. In this context, the application of smart materials provides the building to be a part of the ecosystem in which it is constructed. Under the light of this information, these smart materials have the capacity to be used in architecture to create sustainable environments however since they are not sustainable as materials their contribution takes place in the building phase of the life cycle of a building.

Nine major findings are formulated in this study;

**1.** Sustainable architecture is seen as a vital element of the much larger concept of sustainable development that aims to protect the environment.

**2.** Architects acknowledge the importance of sustainable architecture and this awareness directs them to develop and implement several criteria, concepts and sustainability rating systems.

**3.** Although these approaches enable architects to design more sustainable environments to achieve, a true environmentally sustainable architecture there is a need for new approaches.

**4.** Technological improvements provide new materials with special properties.

**5.** These materials have become current issues in architecture. The application of these smart materials provides new opportunities for different approaches, perceptions and their applications. These smart materials provide new opportunities for architects to realize what they imagine but have not been able to realize.

**6.** As seen in the projects, almost all new approaches and new applications for the use of smart materials are related to the concept of sustainability.

**7.** Smart materials allow architects the opportunity to put into practice ideas that until now have only been considered as possible in theory.

**8.** Although these materials themselves cannot be classified as sustainable since they do not fulfill the necessary criteria, the application of these materials could support sustainable architecture during the building phase.

**9.** In further studies, it is important to conduct, a research examining not only the sustainability supported by the properties of the materials, but also the sustainability of the materials themselves.

As Addington and Schodek state architects should understand and get enough knowledge about smart materials technologies. Only with this understanding, they can use these materials functionally rather than aesthetically. Another important point is that in order to construct sustainable buildings architects should study deeply the environmental conditions thoroughly such as the climatic and geographical conditions in which the building will be constructed. Only if architects bring together this information, the application of smart materials in sustainable architecture can be successful. This success will possible through a deep research of these materials from an architectural point of view with all necessary data including material performances.

In her paper, “Boiling Frogs, Sinking Ships, Bursting Dykes and the End of the World as We Know It,” Chrissna Du Plessis acknowledges that while significant progress has been made in the past decade, architects put themselves on a path of limited possibilities. She mentions Einstein’s paradox, which states that problems cannot be solved by using the same thinking and she comments “the Paradox then is: can we realistically create a sustainable built environment if nothing substantial is being changed with respect to energy generation, building climate conditioning, design, the construction process, operations, and disposal, to name a few things that are not really changing.” She adds “[t]he majority of sustainable construction solutions are not focused on fashioning a new world model that will be more sustainable because the nature of our relationships with the biophysical environment and with each other has actually changed (Du Plessis 2). Du Plessis suggests that Einstein is in fact correct and that architects desperately need to think differently leaning heavily on ecology, biomimicry, and a wide range of other nature-based approaches that have been largely ignored by what may be called mainstream green buildings (Du Plessis 1-4).

In parallel with Du Plessis’s ideas, this study proposes that approach and perception change is possible through technological improvements. New systems and materials to architecture introduced by technologies in provide new opportunities that enable architects to develop new approaches and perceptions. This study emphasizes the need to rely on new renewable energy and materials resources enabled by technological advances in order to create sustainable environments. It is certain that current sustainable approaches will shift to radically new ones. What is now needed is a new consideration of buildings and infrastructure, the materials and construction methods. The first step is to envision an alternative future and then find out how to get there. New approaches that can be useful for mapping such a route are emerging. Especially focusing on learning from nature, following her laws and imitating her materials and processes, and by using technology to realize these.

Depending on the future popularity of the use of smart materials and the visible effects on our buildings, the traditional appearance of architecture will change. Ritter states, “We are standing at the threshold of the next generation of buildings; buildings with various degrees of high technology, which are extremely ecological in their behavior through the intelligent use of functionally adaptive materials, products and constructions and are able to react to changes in their direct or indirect surroundings and adjust themselves to suit” (7).

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**Appendix:**

## GLOSSARY

| | |
|---|---|
| **Actuator** | A control element that is driven by a signal, often electrical, that produces enough power to operate a mechanical element, such as a valve. Common actuator types are electromechanical, hydraulic and pneumatic. |
| **Aerogel** | Aerogel is a low-density solid-state material derived from gel in which the liquid component of the gel has been replaced with gas.<br><br>Generically describes any colloidal solution of a gas phase and solid phase. More typically, aerogel refers to a specific material. |
| **Biomimicry** | The imitation of nature or the study of the structure and function of biological substances.<br><br>Biomimicry is a field of study where robotic mechanisms are based on biologically-inspired models. |
| **Building environmental assessment methods** | These methods differ from the country to country.<br><br>BREEAM and LEED are the most commonly known and intricate methods.<br><br>• BREEAM - Building Research Establishment Environmental Assessment Method is used in United Kingdom.<br><br>• LEED - Leadership in Energy and Environmental Design is used in United States of America.<br><br>• |
| **Cementitious** | Includes cements, limes, and morter which may be mixed with water or another liquid to form a plastic paste, and to which an aggregate may be added. |
| **Catalyst** | Substance that accelerates the velocity or increases the yield of a chemical reaction and that may be recovered at the end of the reaction essentially unchanged. |

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| **“Cradle to cradle”** | A term used in life cycle analysis to describe a material or product that is recycled into a new product at the end of its defined life. |
| **“Cradle to grave”** | A term used to describe life cycle of materials (for example, the management of hazardous waste) from their point of generation to their final treatment and/or disposal. |
| **Cladding** | The outer sheathing of a building that provides the final layer of the envelope. The cladding is exposed to weather and thus needs to be durable while, simultaneously, it is the cladding that is most responsible for a building's appearance. |
| **Composite** | A multi-component material produced when metal, ceramic or plastic materials provide a macrostructural matrix for the distribution of strengthening agents, such as filaments or flakes, throughout the material, increasing its structural performance. Each component, however, maintains its properties. |
| **Dynamic energy models** | Dynamic energy models take into account the ability of thermal mass to modify and delay heating and cooling loads. |
| **Ecosystem** | The interaction of organisms from the natural community to one another and their environment. |
| **Green house effect** | The greenhouse effect refers to the change in the steady state temperature of a planet or moon by the presence of an atmosphere containing gas that absorbs and emits infrared radiation. |
| **Embodied energy** | Embodied energy accounts for all energy expended for production and transportation plus inherent energy at a specific point in the life cycle of a product. |
| **Energy** | The capacity for doing work. Energy exists in several forms, which may be transformed from one to another, such as thermal, mechanical, electrical, or chemical. |
| **Envelope** | The term describes the three-dimensional extents of a building. |
| **ETFE** | A kind of a plastic (Ethylene Tetrafluoroethylene) |

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| **Habitat** | A habitat (which is Latin for "it inhabits") is an ecological or environmental area that is inhabited by a particular animal or plant species. |
| **Health monitoring (structural)** | The comparison of the current condition to earlier conditions to proactively predict potential failure. Most often used for large structures such as bridges and building foundations. |
| **HVAC** | An acronym for heating, ventilation and air conditioning. |
| **Life cycle** | All stages of development, from extraction to production, marketing, transportation, use, and disposal. |
| **Life cycle assessment (LCA)** | A process or framework to evaluate the environmental burdens associated with a product, process, or activity by identifying, quantifying, and assessing its energy and material usage and environmental releases, to identify opportunities for environmental improvements. Extraction and processing of raw materials, manufacturing, transportation and distribution, use/reuse/maintenance, recycling, and final disposal are all considered. |
| **Loam** | Loam is a kind of soil composed of sand, silt, and clay in relatively even concentration |
| **Microencapsulation** | Individually encapsulated small particles or substances to enable suspension in another compound. |
| **Nanotechnology** | The exploitation of the property differences between the scales of single atoms to the scale of bulk behavior. Also, the fabrication of structures with molecular precision. |
| **Nitinol** | A nickel-titanium alloy used as a shape memory alloy. |
| **Organic** | A term applied to any chemical compound containing carbon as well as to a few simple carbon-based compounds such as carbon dioxide. |
| **Photovoltaic effect** | The production of voltage across the junction of a semiconductor due to the absorption of photons. |
| **Piezoceramic** | ceramic materials that possess piezoelectric properties |
| **Piezoelectric effect** | The ability of a material to convert mechanical energy (e.g., deformation induced by a force) into electrical energy and vice-versa. |

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| **Shape memory effect** | The ability of a material to be deformed from one shape to another and then to return to its original shape after a change in its surrounding stimulus environment (e.g., thermal, magnetic). In metals, this phenomenon is enabled by a phase transformation. |
| **Shape memory alloys** | Metal alloys, e.g., nickel-titanium, that exhibit the shape memory effect. |
| **Shape memory polymers** | Polymeric materials that exhibit the shape memory effect. |
| **Thin films** | A large class that is commonly used to refer to any thin amorphous film of semiconductor layers. |
| **Viscosity** | Viscosity is the thickness of a fluid, or how easily it flows. |

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