# Material-Aware Building Design in Responding to Future Needs

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# ABSTRACT

The recent quest for reducing building material ecological impact in parallel to consequences of poorly chosen materials and unsustainable material developments emphasize the need to formulate a comprehensive framework responding to the future. Hence, the conceptual and theoretical foundation of this thesis is brought together around the concept of ‘material-aware building design’ towards a holistic selection of building materials, and considering its future developments.

Accordingly, the ‘material-aware building design’ is proposed by author as a method to examine the influences of sustainability, technological developments, and users and designers’ expectations, as the most influential factors in selection and development of building materials from the past to the present. This research aims to show the target and priorities to material scientists and designers by foreseeing the necessities for the future developments of building materials. Hence, the methodology of research is based on both theoretical and statistical approaches in order to bring building materials possibilities and challenges in the design procedure. Consequently, the outcome of this thesis would be beneficial for both designers and architects in order to deal with complex challenges, and improve their designs in terms of environmental responsibility, social wellbeing, and adaptability to the future needs.

As a result, by the evaluation of the key factors in the selection and development of building materials, it can be assumed that in the future, the sustainability issues with the assistance of technology and designers would direct building materials developments considering environmental requirements and users' expectations. Therefore, the focus should be on the development of engineered, smart, nano, and bio-based building materials. Additionally, the digital design and construction technology would develop innovative, efficient, and lower cost building design and construction techniques. Likewise, the advances in material experimental, tactile, and spatial properties, as well as immaterial stimulus could provide new experiences.

**Keywords:** Material-Aware Design, Sustainability, Designers and Users’ Expectations, Technology Developments, Future materials

# ÖZ

Binalarda kullanılan malzemelerin eko-sisteme olumsuz etkisinin azaltılması, kötü ve sürdürülebilir olmayan malzeme gelişimlerinin engellenmesi ve geleceğin buna göre programlanmasını gerektirmektedir. Bu nedenle, kuramsal ve kavramsal bir temele oturan bu çalışma, bina malzelesi ile tasarımı arasındaki ilişkinin farkındalığında yapılacak malzeme seçimi, ve yakın gelecekte olası malzeme gelişimlerini dikkate alınarak incelenmiştir.

Yapılan çalışma ile, malzeme ve bina tasarımı arasındaki interaktif ilişkinin ortaya konması için önerilen metot, malzeme seçimi ve gelişiminin tarihsel süreç ve gelecekte olası gelişimi, sürdürülebilirlik, teknolojik gelişmeler, bina kullanıcı ve tasarımcı beklentileri gibi kriterler dikkate alınarak geliştirilmiştir. Bu araştırmada amaçlanan, malzeme bilimcleri ve tasarımcılara yakın gelecekte, malzeme gelişimi ile ilgili öncelik ve hedefler konusunda yol göstermektir. Tasarım sürecinde malzeme ile ilgili gelişim alternatifleri ve tasarim problemleri kuramsal ve statistiksel bir metot kullanılarak belirlenmiştir. Geliştirilen metot, tasarımcı ve mimarların, çevresel ve sosyal sorumluluklarını yerine daha rahat getirip, yakın gelecekteki olası gelişmelere daha kolay entegre olmasını sağlayacaktır.

Geliştirilmiş metot neticesinde ortaya çıkan sonuçlara göre, yakın gelecekte oluşacak malzeme gelişimleri, çevresel faktörler ve kullanıcı beklentileri ışığında, sürdürülebilirlik kavramı ekseninde, teknoloji ve tasarımcı beklentileri dikkate alınarak gelişim gösterecektir. Buna göre malzemeler, mühendislik ürünü, akıllı, nano ve biyo-bazlı inşaat malzemelerinin önem kazanması beklenmektedir. Dijital tasarım ve yapım teknolojilerinin gelişmesi, yenilikçi, etkin, düşük maliyetli bina tasarımlarına olanak sağlayacaktır. Paralel olarak, gelişmiş malzemelerin, doku, mekansal özellikleri yanında, maddi olmayan enerji bazlı malzemelerin gelişmesi olasıdır.

**Anahtar Kelimeler:** Sürdürülebilir, Tasarımcı ve kullanıc beklentileri, Teknolojik gelişim, Yenilikçi malzemeler.

**TO MY FAMILY,**
for their unconditional love

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At the end, I would like to dedicate this thesis to my family who encouraged me to broaden the horizons of my imagination and supported me through my education. I hope that dedicating this thesis to them, even though it is not much, could return a bit of their love and kindness.

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# INTRODUCTION

## 1.1 Notes on Crisis of New Materiality

Today, with the spread of the process of globalization and the flow of technological, social and economic developments, we are facing with rapid changes in our natural and built environment. One part of these changes is allocated to the new materiality in our built surroundings that have turned our habitat to a space for consuming unlimited numbers of complex and fashion-oriented materials and products. This materiality is tied up with our everyday life, which defines the levels of comfort and pleasure in our living environment and most importantly from an environmental perspective plays an important role in energy and resource consumption, creation of waste, pollution, and other environmental challenges.

Designers and architects are in the central position of determining and directing new materials that enter into the market every day. Hence, as recent attempt by architecture society is looking for a comprehensive design practice, the 'material-aware building design' is proposed as an important concept leading to environmentally responsible, human-based and adaptable design. Besides, most of the research concepts regarding the material-aware design are relatively new architectural challenges in the field of building design that need to be discussed profoundly.

## 1.2 Subject Matter and Problem Statement

With the advances in the field of material innovation and regarding to today's living requirements, designers are utilizing new materials in their design. The innovative materials give architects higher ability to support their designs rather than traditional materials. Moreover, these materials due to their unique properties and an easier fabrication process provide new concepts for singular or multiple functions in responding to the needs for cheaper and flexible design. Likewise, because of their lightweight and smaller design, they are considered as good examples of energy efficiency, resource conservation, and reduction of waste. As a paradox of the above arguments, in one hand, manufacturing process of these materials and their synthetic components could cause environmental problems, and on the other hand, the new materials cannot fulfill the humans' need to sense the warmth, convenience, and welcoming of the traditional materials. Due to the importance of the users' need to feel the familiar sense of the natural and traditional materials in their living surroundings, and in order to increase the human well-being, material and texture professions have been trying to give natural texture to the new synthetic materials, however this strategy was not completely successful. As a solution to these challenges, designers and material engineers should be directed towards new material-aware building design framework according to needs of today and future. To do this, there is a need to define the borders of users and designers' expectations with technological developments, as well as sustainability challenges in order to move towards responsible architecture design.

## 1.3 Aim and Objective of Research

Pervious literatures have searched for diverse concepts around the subjects of building materials, such as building material interaction with form and structure

(Mozaikei,2009), the methods of material selection (Ashby,2004), or building materials in the realm of environmental sustainability (Bege,2009; Araji & Shakour,2013) while the concept of ‘material-aware building design’ as a comprehensive framework have not been considered yet. Besides, the previous studies do not interpret the important constraints on building material developments according to our future needs. Therefore, the author proposed ‘material-aware building design’ as a new design framework, and sustainability, technology developments, users’ need and designers’ expectation as the most influential factors in the selection and development of materials, as its major criteria. Considering the proposed framework, the main aim of this research is to show the target and priorities for selection and development of building materials to material scientists and designers in order to direct them according to our present and future needs. It also aims to illustrate the issues that should be addressed in material-aware building design for architects and designers in order to achieve more innovative, human-based and sustainable building designs. In this way, this research is going to examine the historical and contemporary developments in material evolution, to foresee the necessities in the future and opening up new ideas to identify the future direction. It introduces recent innovations through building material technology, which develops new concepts and solutions towards an adaptable and sustainable future. In due course, the initial question of this research would be, ‘What kinds of building materials are suitable for today and future developments?’

The other research questions are organized in the following, which help to achieve the goal of this thesis.

- How innovations in building material technology would affect our designs?

- What are the differences between users and designers’ expectations?
- What is the role of material development to achieve more sustainable and human-based approach in design?
- What would be our priority and limit in selection of building materials?
- How the role of sustainability, technology, designers and users changed from the past to the present?

These questions are answered during this study and through the concept of the material-aware building design.

## 1.4 Research Methodology

In order to achieve the research objectives, this thesis is based on both qualitative and quantitative research family. One part of the data collection technique is allocated to literature survey through the books and articles in order to collect theoretical data and the other part is allocated to statistical approaches in order to measure and compare material development indicators in a scientific way. The author defined sustainability, technology developments, users’ needs and designers’ expectations as the main criteria of ‘material-aware building design’, and tried to get a quest of the past and present to foresee the necessities of building materials’ developments for the future (Fig 1.1). The technology driver encompasses construction technology, material processing, construction materials and design technology, and sustainability driver involves environment, economy, society, and functional and design requirements. It should be noted that the selection of these criteria was achieved through collecting principles from different conceptual theories as one multipurpose framework for selection and development of building materials.

As a method, the author developed hierarchical structure and hierarchy evaluation method in order to represent 'material-aware building design' main criteria through their sub-criteria in a beneficial way, and to measure the relevant weight of each criterion up to the corresponding period. In this method, the main criteria and its sub-criteria are ranked as numbers and percentages according to their possibility and ignorance for each period, and the results are presented in diagrams. The results are beneficial to compare the influences of sustainability, technology developments, users' needs and designers' expectations in selection and development of materials from past to the future. Thus, the proposed method is in response to the existing paradox as the main challenge of material engineers and designers, which must be considered in the building design procedure in order to answer our today and future needs and expectations on materials developments. Furthermore, analysis of some contemporary projects helps with better understanding of the contemporary attempts in the field of sustainability, technology developments, users' needs and designers' expectations. As a result, these steps lead us to a prospective achievement in directing the selection and development of building materials.

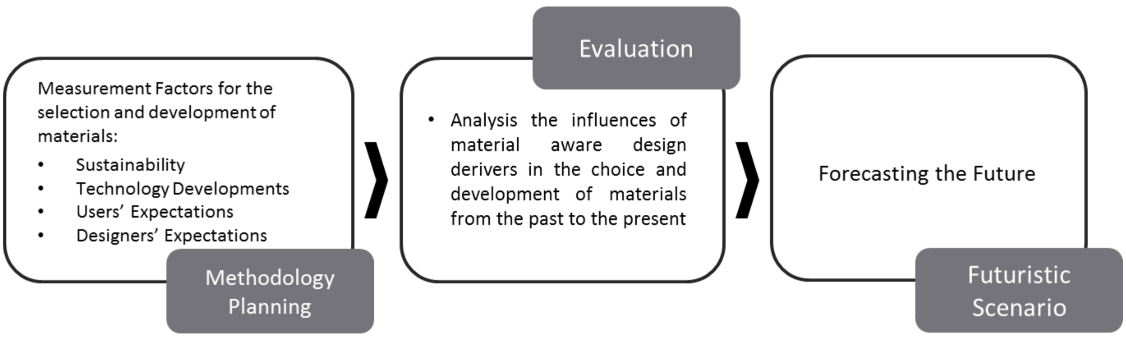


Figure 1.1: Research Methodological Framework

## 1.5 Organization and Structure of Thesis

This thesis allows the reader to achieve an outstanding knowledge on the concept of material-aware building design in responding to future needs. Five chapters make up the main structure of this thesis. Following descriptions are a short summary of the structure of this thesis.

Chapter 1 provides the basic information about the orientation and structure of the research. It begins with introducing the crisis of new materiality in our living environment, and the paradox that it causes between environmental issues, technology development, users' needs and designers' expectations. Then it follows with aim and objectives of research and its methodological framework in order to solve the problem.

Chapter 2 is set out as a general overview of the material revolution, which discusses the source and development of building materials from the prehistoric times to the industrial revolution, and from the rise of the modernism until today's materials developments. Through this achievement, it seeks to examine factors, which affected selection of building materials during the long history of materials revolution until today. Additionally, the importance of the role of sustainability, technology developments, users and designers as the main factors, have been surveyed.

Chapter 3 begins to lay out the interpretation of the theoretical and technical foundation of the concept of material-aware design, and then it illustrates all of the four criteria as a guide to material selection and developments. The sustainability section introduces the 'environmental issues, 'economy and lifecycle cost, 'social and cultural issues' and 'functional and design requirements' as the most important challenges related to the development and selection of sustainable building materials. At the end, it will introduce ‘Green building materials’ and ‘Cradle-to-Cradle certificated materials’ as the major contemporary solutions for building material sustainable development. The technology section, at first, provides an insight into innovative materials as the source of future developments. In this part, biotechnology and bio-inspired materials, engineered and high performance materials, smart materials and intelligent systems, as well as the nanotechnology influences on material development are evaluated. Furthermore, the influences of technology through material design, fabrication and modeling considering some of forward-looking projects and technologies are introduced, which create the foundations of the future developments.

In order to achieve user's satisfaction, there is a need to define their expectations from building materials. Accordingly, the third section is allocated to the ‘users’ expectations from building materials developments’. In this section, the effects of sensory, technical, functional, and spatial attributes of materials on users’ satisfaction, as well as their physical and psychological health are considered. Additionally, the influences of intangible factors such as culture, identity, values and beliefs are demonstrated. The last factor is ‘designers’ expectations from material developments’, which examines the challenge of designers in material selection considering function, shape, material and process. Furthermore, it includes the evaluation of a questionnaire survey of designers’ expectations in order to give a wider and realistic perspective.

The chapter 4 evaluates all the data gathered from the past until present, in order to foresee the future possibilities and challenges of building material developments. The first section is allocated to theoretical analysis of data based on pervious discussions about development of materials. Therefore, the environmental crisis, challenge of human and technology interaction, advances in material developments through constructional materials, material fabrication and immaterial influences are discussed profoundly. In the second section, the author used from the hierarchy evaluation method and by computing the numerical value for each criterion tried to measure its level of importance from past to the future. Therefore, the influences of technology, sustainability, designers and users' expectations in the selection and development of building materials from the prehistoric times to the future are evaluated and presented in a line chart. Moreover, the levels of contribution of each criterion in response to the whole system are calculated as percentages and shown in another diagram.

At the end, chapter 5 provides a summary conclusion of the discussions and evaluation of the concept of material-aware building design in response to future needs.

# Chapter 2

# MATERIAL REVOLUTION: SOURCE AND DEVELOPMENT OF BUILDING MATERIALS

The main aim of his chapter is to accomplish the theoretical background of the building material revolution. It examines the factors that from prehistoric times until today affected the designers' selection of materials. Through this achievement, the most significant revolutions in building materials and its influences on building design are considered, which help to clarify the future of material developments.

## 2.1 An Overview of the History of Building Materials from Prehistoric Times until the Industrial Revolution

The history of materials referred to the way that human modified its environment to build a safe shelter against natural forces. Early humankind left caves to start agriculture and food production. Since then, some of very early shelters were built from vegetal materials (e.g. canes, palms, etc.).  In the Neolithic times (8000 - 5500 BC) with beginning of real civilization and village life, human achieved advances in farming, art forms, architecture, tools and weapons (Wright, 2005). With changes in social structure, they needed for resistant materials in order to provide the basic need for a permanent shelter to build a community. Accordingly, human moved away from the imitation of nature and subterranean settlements to freestanding man-made structures and began his career as a builder (Love, 2013). At first, human started to use wood, mortared rubble, mud, reed and other available materials in building constructions, and later with a higher level of civilization and developments in construction technologies, human produced hand modeled mud bricks (Niroumand et al., 2013a).

By changes in human evolution, the ancient builders started to recognize the efficiency and durability of materials for their required purpose. They started to manufacture the materials to attain their desired quality and increase the speed of construction, which has become the first signs of artificial and manufactured built environment. Thanks to the production of ‘form molded mud bricks’ with standard cubic form and size, spaces changed from oval to more rational rectangular forms (Fig 2.1) (Love, 2013). Furthermore, the use of standardized devices and the increase in the speed of brick production helped with the development of the ancient material production system. About 3000 BC, with manufacturing of burnt brick human achieved a higher strength of brick than its dried one. Application of burnt brick needed to skilled work and due to its expensive manufacturing process in the early years, it was just used for important buildings. Afterwards, building materials and construction technique became a separated skilled work for a group of builders and the selection and production of materials has become according their ability and expectation (nature, rulers) (Wright, 2005). The importance of material developments in early civilizations such as Stone Age, Iron Age, and Bronze Age is obvious from their archeological identification according to their dominant material mystery (Oxman, 2010). During these ages, in addition to resource availability, climatic, technical, social and practical factors were determinant in the selection and development of materials (Love, 2013).

In the history of humankind's evolution, with an increase in power of humanity, they obtained the ability to call for huge amount of resources for their constructions and other fields of consumption (Wines, 2000). Developments in the quarrying industry of Egyptian, Greek and Roman civilizations were another important event and since then, human started to change the face of the earth. Humans began to cut blocks of stone from bedrock into a regular form, and since then, the first structural stone was built. The 'dressed block of stone' was used as one structural unit (e.g. Lintels, columns, frames, piers, etc.) or to make up each structural unit (e.g. Vaults, domes, columns, etc.) (Wright, 2005). Egyptian, Greek and Roman empires used the stone as a permanence material mainly for monumental structures such as pyramids, tombs and temples in a dominant position to show the power of their empires or sacred purposes (Gagg, 2012).

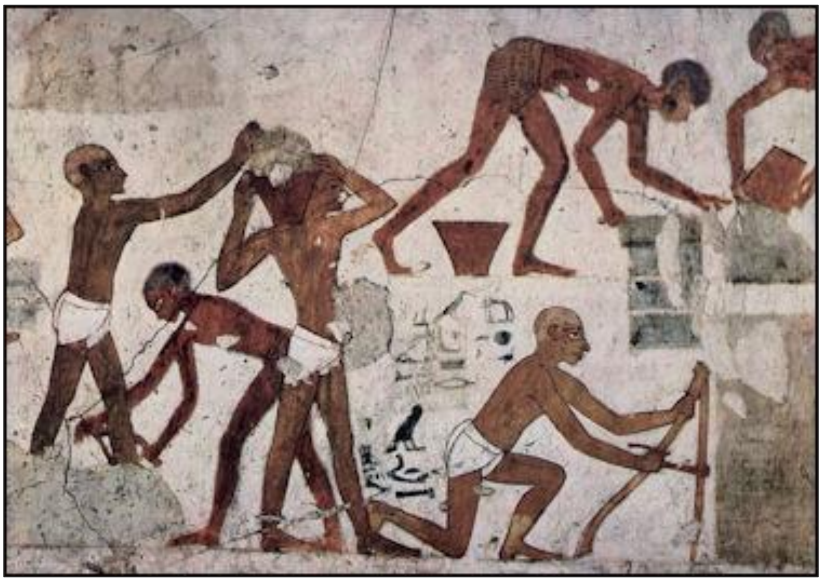


Figure 2.1: Ancient Egypt pyramid building workers; brick making. Source: (Wright, 2005; URL1)

In the first century BC, the invention of Roman concrete from slaked lime, water, sand and volcanic rock and other substances was an influential development in ancient building construction. The Romans utilized concrete as an early composite material in the construction of walls, foundation and roofing (Beylerian, & Dent, 2005). Additionally, lime-based materials and gypsum were used as a mortal or plaster on walls or floors to provide smooth surfaces and for humid protection (Wright, 2005). The revolution of architectural glass also comes back to the Roman culture. In early applications, it was used as a decorative luxury material in the cathedrals, but later during the eighteenth century glass window has become affordable for all buildings for bringing light inside, as well as controlling the inside climatic condition. Painted or glazed clay tiles also were used as decoration and finishing material from the ancient times with symbolic, social or religious motifs, which developed in the European and Islamic culture until today (Gagg, 2012).

Gradually, builders emerged diverse tools to manipulate materials according to their ability for structural and constructional purposes. For instance, the Greeks used from massive stone columns in post-and-lintel structure system, while the Romans developed arches to solve their need for wider spans. The pointed arch redirected the weight of stone into legs and with assistance of the domed roof led to an increase in the levels of lightness and elegance of the Roman's buildings (McClure & Bartuska, 2007). Furthermore, the Romans were aware of the heavy nature of their building materials to use from lighter materials in higher levels of building (Fig 2.2). During the history of building design, designers, however with limited choices of materials by adding ornamentations, changing the color, size and proportion as well as, covering the surfaces or leaving them in their pure way tried to affect the spirit of space in order to become unattainable or in human-scale. Later, the shift from secular and naturalism philosophy of the Greek and Roman empires to the divine philosophy of the Middle Ages caused powerful changes in art and architecture tendencies. Medieval cathedrals with their "rationalization" and clear stone masonry provided a sense of divine power and the Renaissance elegant symmetry, proportion, and use of expensive materials and ornamentations with marble, colored stone, stucco and gliding provided the sense of stability and wealth in a more secular way. In the following centuries, the western Baroque with an expressive approach, and the revival of the historic architecture at the turn of the twentieth century continued this progress of stylistic approaches in design (Gelernter, 1995).

Figure 2.2: Inside the Pantheon (2nd c.); on the lowest level travertine, the then a mixture of travertine and tufa, then tufa and brick, then all brick was used around the drum section of dome, and finally pumice as the lightest and porous materials for the ceiling of dome. Source: (URL2; URL3)

The environmental motivations for the selection of materials in the past was in response to climate, topography and regional situations, and human notions of nature was along with weakness and inability of human in front of the power of the nature. For this reason, in prehistoric period the buildings were devices for human protection from natural forces or later sacred monuments for the worship of the nature (Wines, 2000) (Fig 2.3). In different historical time spans the interconnection and the amount of benefits of man from nature was variable and had too many up and downs. In the realm of connection with nature, there are ancient cultures or nature oriented philosophies that are sources of architectural designs and in a continuous interconnection with nature, such as Far East traditional architecture or regional vernacular buildings with less contribution in advanced architecture and construction developments (Wines, 2000).

Figure 2.3: Stonehenge; a historic site for celebration of nature, Salisbury Plain, England c. 3200-1600 BC; Source: (Wines, 2000; URL4)

Over the long history of materials' revolution, designers and builders were limited to an empirical understanding of the material properties, and knowledge of materials was realized through experimental and optical investigations (Addington & Schodek, 2005). For instance, the quality of the stone was examined by creaking caused by pressure, smell, color or scraping by knife, as extrinsic discovery techniques (Berge, 2009). Therefore, the functional properties of materials had less importance in the design process. However, the progressive experiments in understanding of properties and constituents of materials slowly resulted in further advancement in materials functionality.

## 2.2 Material Evolution since Industrial Revolution to the Rise of Modernism

At the end of the $18^{th}$ century, the industrial revolution has become the most important development in the history of production and construction industry, which led to mass production and rapid consumption of materials and resources. Developments in energy resources, steam power, mechanization of factories and ease of production influenced the economic, social and technological structures of the society (Prudou, 2008). Consequently, with rapid civilization and the immigration of people to cities, the constructional properties of materials got their higher amount consideration and the designers tried to engineer materials to achieve their maximum potentials for new construction of high-rise buildings, bridges, tunnels and stations (Addington & Schodek, 2005).

On the other hand, the crisis of World Wars (1914-1918; 1939-1945) as the result of political clashes also provided a new direction in building material and construction. Because of the war and its problems, there was an emphasis on manufacturing industry, and subsequently, low cost and new mass-produced houses for military and homeless people were developed. The prefabricated production industry and other new technologies were the legacies of wartime (Smith, 1998). After the World War II, the war technology and materials provided by the army have emerged widely in the building construction industry. Accordingly, after the devastation of the war, it was an era of progressive transformation into a new world (Curtis, 1996). The changes in politics and social metabolism, as well as economic growth were clearly manifested in building construction and technological developments of that period.

From the benefits of mass production of steel industry and advanced structural steel framing, the old masonry structures transformed into the frame structure. Hence, by utilization of steel framing, reinforced concrete structures and new technological equipment such as elevators and mechanized systems, the construction of open plan and high-rise buildings has become possible (Vaclav, 2005).

Figure 2.4: The first skyscraper with load-carrying frame of steel structure, Source: (Vaclav, 2005)

During the postwar period, building heavy masonry cladding replaced by a lightweight panel or skin made of metal, glass or concrete, and the new possibilities of the curtain wall system encouraged the separation of structural frame from exterior cladding, which later changed to double skin cladding to promote environmental and visual comfort of the buildings (Prudou, 2008).

After the industrial revolution, the selection of materials was according to functional needs, and architects got benefits of new materials and new structural systems to create functional forms. The mass production systems, modular, repetitive, and high-rise building types were the rational achievement of modern style. The craft-based lessons together with academic use of materials combined with new methods of construction and technologies (standardization) started from the Bauhaus school (1919-1932) (McClure & Bartuska, 2007). Afterwards, the most focus of designers was on structural properties of materials rather than decoration of form. Therefore, manufactured material pieces with modular and component structure, and ability to assemble/disassemble have developed that were more adaptable to change; however, their wasteful production and redundancy caused damages to the natural environment (Oxman, 2010).

Jennifer Siegal from an architect's point of view argued:

> "We no longer believe in the monumental, the heavy and static, and have enriched our sensibilities with a taste for lightness, transience and practicality… we must invent and rebuild ex novo our modern city like an immense and tumultuous shipyard, active, mobile, and everywhere dynamic, and the modern building like a giant machine." (Tanzer & Longoria, 2007, p.124)

The modernist architects under the auspices of technology with utilizing new materials and technologies and spreading them through their designs were overpowered as leaders of new modern lifestyle. Buildings were to follow the automobile analogy like Henry ford machine assembly line and modernist designers tried to fit users in their functional systems (Redstrom, 2006). The opportunities afforded by modernist to create high-rise buildings with vast open spaces, maximum light and minimal structure have expressed in the 'Glass Skyscraper' of Mies van der Rohe. Therefore, steel and glass developments, in addition to possibilities of climatic control systems provided the ground for the introduction of 'international style', which developed as an international context for any climatic situation (Fig 2.5).

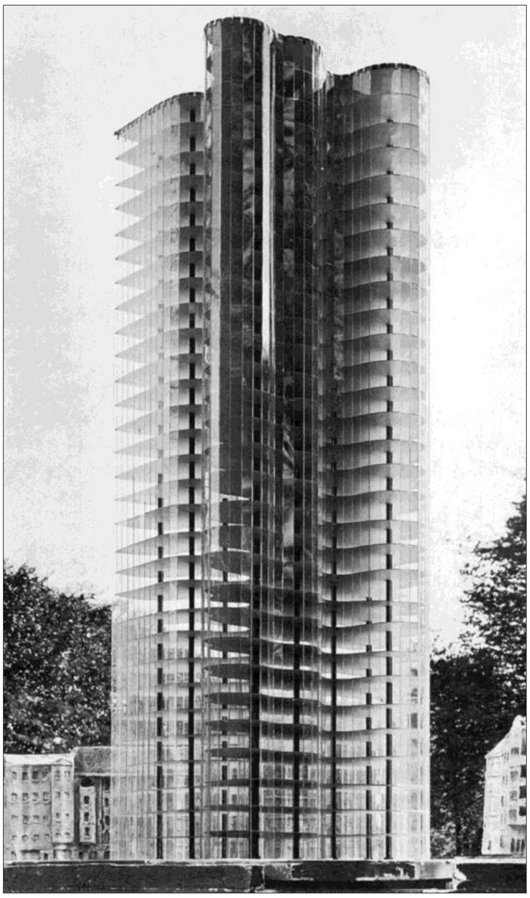


Figure 2.5: Glass Skyscraper model by Mies van der Rohe (1922); Source: (URL5)

As a result, the functionalism of modern movement led architects to design exposed structure, simple geometry and ornament free forms (Gagg, 2012). Hence, the change from the world of craft to machine-based design was in response to the demands and opportunities of the industrial age, hand-in-hand with materials and technological developments, while the notion of environmental sensibility, culture and climate in modernism, and other common styles were less important. Thus, this approach had faced failures due to its lack of consideration on users, cultural and regional diversities, and environmental issues.

Generally, in a continuous revolution from the past, the twentieth century continued by introducing of new styles in association and against the modernism movement.

The table 1 presents the most influential styles of the twentieth century with a detailed description of their characteristic and construction materials. Accordingly, each style is associated with certain materials, colors, decoration and form. The improvement of social life in bigger communities and the appearance of design movements encouraged other individuals to follow styles like fashion so fast. The styles have developed under different intellectual, social, economic, cultural, technological, symbolic, and religious conceptions that influenced society to follow their characteristic in design (McClure & Bartuska, 2007). Therefore, new building materials and technology developments in manufacturing, construction and structural systems are one of the major motivators of stylistic approaches in each period. As a result, the table 1 shows that most of the twentieth century styles were influenced by available construction materials and technologies, which were manipulated by designers in diverse ways to define the specific characteristic of their styles.

Table 1: Analysis of the main styles and building materials in twentieth century

| 1800 (Industrial Revolution) - 1900 | Style Characteristic | Structural System | Façade and Ornaments | Interior Elements & Materials |
|---|---|---|---|---|
| **Revival (historicism)**  | Neo Gothic, Neo classicism, Baroque and Victorian styles | Masonry structures, stone or concrete foundation | Stone, brick, terracotta and tiles | Marble stone, wood, patterning and gilding effect to walls, decorative flooring mosaics, and ceiling with decorative elements |
| **Arts and crafts movement (1860-1925)**  | Functional plan, respect to traditional aesthetics, built in cabinets, shelves and beamed ceiling, rejection of machine products | Craftsmanship methods of construction; Masonry structures, stone or concrete foundation | Brick and tiles, wood and stone | Honestly use of materials, dark Wood craving wallpaper, wooden parquet flooring |
| **Art Nouveau style (1888–1905)**  | Curve shape of organic forms, sculptural forms, decorative motifs in façade and interior | Concrete or steel frame structure (post-beam structure), curtain wall system, concrete foundation | Plate Glass, terracotta and masonry facade, cast iron ornaments | Decorative elements, gypsum, glass and iron, stained glass and iridescent glass tiles; decorated wallpaper and carpet |
| **The Chicago school (1880–1900)**  | The first floor functions as the base, the middle stories have little ornamental detail, the last story have more ornamental detail, capped with a cornice. Chicago window: large fixed center panel window with a grid pattern | Concrete and steel frame structure (post-beam structure), Concrete foundation | Plate Glass, terracotta and masonry facade, cast iron and terracotta ornaments | Plaster, paint, and finishes such as stencilling, marbling, and graining, undecorated surfaces |
| **De Stijl (1917-1931)**  | Pure abstraction of form and color, (primary colors), visual compositions to the vertical and horizontal directions with straight lines and rectangular planes (architectural and structural elements), emphasizing the fluidity and continuity of space | posts and beams structure, foundations and the balconies are made of reinforced concrete and steel profile, floors are supported by wooden beams and steel girders with wire mesh | Plasticity of the facades, adoption of glass, steel, grey stucco, window frames and doors were made from colored wood | Flexibility of its spatial arrangement, colors are used in small planes and bold blocks, built-ins and fashioned sliding panels, new furniture(red/blue chair) without padding or comfort with painted wooden ends |
| **Art Deco (1920)**  | Influenced from cosmopolitan luxury, industrial power and progress; semi abstract geometry involving horizontal and zigzag lines and dynamic streamlining | Concrete and steel frame structure (post-beam structure), concrete foundation | Stucco, concrete, smooth-faced stone and terracotta façade. stainless steel and aluminum cladding with glass blocks and decorative opaque plate glass | Use of exotic hardwood, ivory, leather, glass and bronze with motifs of lotus-blossom, and rising sun in interior. The classicism, African and Egyptian decoration. use of plastic, steel and aluminum in furniture |
| **International style (1930-1940)**  | Expression of volume, simplification of form, functionality, rejection of ornament, honest expression of structure (machine aesthetic), acceptance of industrialized mass-production techniques, ignore of regional climate and cultural differences | Concrete and steel frame structure (post-beam structure), double skin facade, concrete foundation | Truth of materials, adoption of glass, steel and concrete, plaster and aluminum, wide and large windows in broken horizontal rows forming a grid, metal casement windows, float glass | Proportion and separating partitions in interior, smooth and un-textured walls, colors tended to be in black, white, gray or beige, travertine marble and polished stone surfaces, leather and steel simple and modular furniture pieces with round, sinuous and elegant lines and exposed structure |
| **Late modern (1950-1970)**  | Formless and pure design, more plastic design by irregular forms, exposed materials, | Concrete and steel frame structure, use of advanced form-active and surface-active structures, concrete foundation | Titanium and steel panels, concrete slabs, reflective and coated glass, pattern in façade to make more variation | Using different finishing materials, color and patterns such as Plaster, painting, marble and stone, metal and wooden surfaces in simple and undecorated arrangement |
| **Post modern era** (post modernism, high-tech, Deconstructivism **(1972-2000)**  | Rejection of strict rules of modernism, complexity, fusion of form and function, ironic and symbolic design, in some cases regional identity, context and texture consideration | Concrete and steel frame (post-beam structure), concrete foundation | Plate glass, concrete, brick and terra cotta decorative façades, bronze or stainless steel embellishments | Plaster, painting, and finishes such as marble and stone, decorated surfaces with symbolic or traditional motifs in interior; exaggeration of motifs in new forms |

Note: the table is based on many sources; Ozay, 1998; Vaclav, 2005; McClure & Bartuska, 2007; Mozaikci, 2009; Ashby & Johnson, 2010

## 2.3 Twentieth Century: The Age of New Materials and Technologies

A great number of new classes of construction materials developed among the twentieth century. At the beginning of the 20th Century, the glass production moved away from hand-blown to machine manufactured glass, which reduced glass losses and cost. Afterwards, the invention of float glass for glazing in the 1950s, and the production of “fiber optics” in the 1970s, led to vast applications for glass (Beylerian & Dent, 2005). Moreover, the rapid developments in manufacturing of light metals such as titanium, magnesium and aluminum have provided new applications of metallic alloys such as high-performance glass coated with thin films of metal and building cladding (Fernandez, 2004).

In parallel to this, material scientists started to engineer the properties of natural materials like wood to avoid the problems of rot, fungal and insect attack. Therefore, engineered materials such as the laminated wood and plywood developed at first of the twentieth century (Gagg, 2012). On the other hand, with the possibilities provided by the development of synthetic polymers, there were impressive changes in art and architecture, and even fashion (Fig. 2.6). Plastics are cheap, flexible, in diverse colors and levels of transparency, or other embedded characteristics that are not available for other classes of materials (Karana, et al., 2014).

As mentioned previously, the human accessed to create material with component parts such as concrete by the Romans since long times, but it was not until the twentieth century that technological advances led to create a countless number of composite materials and products. Composites are created from traditional materials with new agents such as medium-density fiberboard (MDF), or new materials

Figure 2.6: Kartell company plastic furniture by Giulio Castelli (1949) Source: (Karana, et al.; 2014; URL6)

manufacturing technologies in micro scale, mostly linked with possibilities of fibers as component in the design of materials such as carbon-fiber reinforced plastics (CFRP) (Fernandez, 2004). In contrast to restriction in form and space that are created by conventional, modular and angular building materials, the self-supporting structure of composites increases the dynamic and integration of spaces (Fig. 2.7) (Gagg, 2012).

With changes in the industrial material world, the twentieth century was the age of design for an industrial society. Architects designed to get benefits from new materials and construction technologies. In the early of the nineties, the technology of computer aided design (CAD) has become manifest and architects started to create complex free forms. Later, the advanced digital design technologies have led to new directions in the evolution of spatial structure, innovative use of materials, and digital fabrication (Oxman, 2006). In these years a few designers like Buckminster Fuller were seeking to a new relationship of object and material and left us an intellectual legacy about light weight structures and material optimization for today's world. Eventually, the Buckminster Fuller's lightweight dome structure –known as the Bucky Fuller style- has become famous for its efficient and innovative design (Fig 2.8) (Wines, 2000).

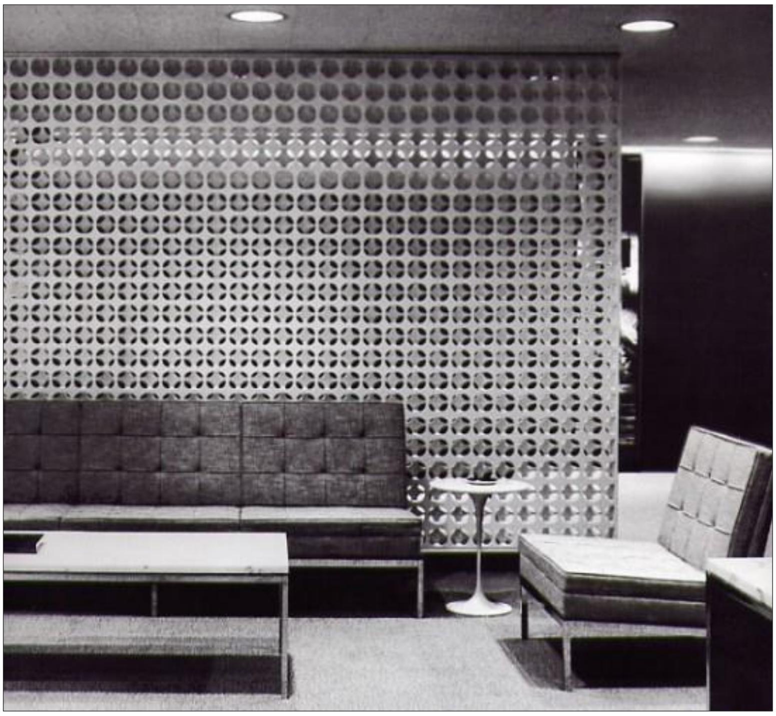


Figure 2.7: Composite CONTINUA Screens by Erwin Hauer; Look Magazine Headquarters, NY, 1960; *Source:* (Karana, et al., 2014; URL7)

At the end of the 20th century with threat of oil supplies and industrial pollutions, the energy conservation and environmental factors began to spread as an international agenda. This pushed for energy and resource efficient strategies in building design considering energy, land, water, climate, and materials (Gissen, 2002). Thus, with an increase in environmental concerns, design principles turned into design for the environment, people and nature and this approach has become one of the reasons for sensibility in material selection and interest in using environmentally preferable materials that has continued up until now.

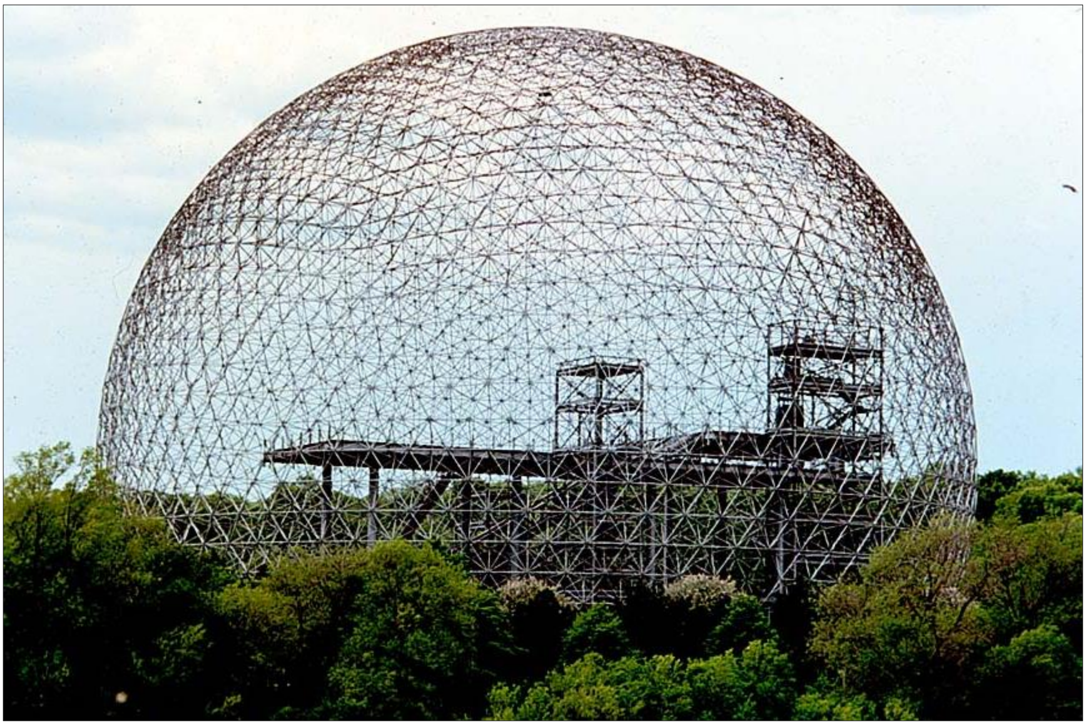


Figure 2.8: Buckminster Fuller' Montreal geodesic dome (with structure of steel and acrylic cells); 1967.Source: (URL8)

## 2.4 Today's New Materiality Influence upon Design

Our today experience of materials is more diverse than ever. According to McClure & Bartuska (2007), our human-modified world is labeled with artificial, synthetic, composite and pre-fabricated objects. The new materiality influences on design develops a complex relationship of science, technology and design. The development and possibilities of this age involve innovations in both high-tech and traditional construction materials, which brought unlimited variety of artificial and natural materials for designers. Hence, the evolution in materials behavior and characterization is an outcome of the interaction between material science and engineering, which changed the personality and reality of materials into innovative and high-performance materials. Additionally, digital design and manufacturing are bringing new possibilities for mass-customization of materials, which lead to the uniqueness and variety of construction materials, as well as new methods of building construction that will be discussed in the subsequent chapter.

Nowadays, architects moved away from the limits of static materials into dynamic characteristic of new materials. The improvements in material science and engineering technology in both macro and micro scale changed the performance of materials and brought new properties such as the ability to be bent, twisted, hammered, rolled, and wrought for materials. Accordingly, designers achieved the ability to create three-dimensional and curve shape forms by engineered woods, plastic or metals (Mori, 2002). An example of this is ‘Plopp stool’ by the Oskar Zieta (Fig.2.9). In production of this stool by the help of FIDU technology, thin sheets of metal are welded together to create a smooth and lightweight surface (Karana, et al., 2014).

Figure 2.9: Plopp stool by Oskar Zieta, Source: (Karana, et al., 2014; URL9)

On the other hand, smart materials and nanotechnology increased materials performance and intelligence, and brought unique applications and new functional opportunities for materials (Addington & Schodek, 2005). Additionally, by advances in texture design (e.g. three dimensional, dynamic, lightweight, flexible and strong textures) contemporary designers gained ability to give emotions to their design, and the interior of the houses has become full of vitality and energy in responding to clients' individual and ambitious expectations (Gagg, 2012). From the environmental perspective, engineers are searching for sustainable technology solutions. The lightweight, green, bio-based and effective materials are some of the contemporary solutions, which will be discussed in the later discussion of this thesis. In general, our contemporary building design is measuring according to its respect to humanity, environment as well as, from the window of innovation, adaptation and intelligence, which opened discourses on material-aware building design for future developments.

## 2.5 The General Conclusion of this Chapter

Over the long history of humankind's evolution, with increases in power of humanity, human beings obtained the ability of calling for huge amount of resources for their constructions and other fields of consumption. At the beginning, the prehistoric builder's selection of material was according to the availability of material, regional and practical issues, while with higher levels of civilization, and production of manufactured materials such as burnt brick, advances in extraction of raw materials, and construction tools and techniques, multiple choices have become available. In a general overview, during the history of craft-based materials, there has been just sensory and experimental use of building materials, while in recent decades, it changed into consideration on material science and engineering. Today, architects are searching for a multiple properties of materials, while the ancient builders just gained the ability to manufacture materials according to their singular needs. Additionally, the new materiality resulted in advances of industrial and academic research that led to new interest in technological potentials to develop innovative materials.

Consequently, with opportunities that material and technological innovations bring to our contemporary design, we are moving to somewhere that all imaginable ideas and structures are becoming buildable; however, the environmental, cultural and humanistic issues are the main forces for elimination of this process. Although the new ideas are continually transforming our lifestyle and culture, in the design history always there is rejection of new materials and coming back to traditional or natural materials. As a result, during the history there are inspiring ideas for designers working a thousand years later to refresh their concepts in searching for cultural identity or vernacular deigns patterns, and informative lessons from the past about how people dealt with natural and traditional fabricated materials and their low-tech solutions to get a balance with nature. To sum up, the influential factors that affected the selection and development of materials from the prehistoric times to the present are provided in a summary table (Table 2).

Table 2: Influential factors in selection and development of materials from the prehistoric times to the present

| Time period | Architecture | Building materials and structural system | Influential factors in selection of materials |
|---|---|---|---|
| **Prehistoric times** | Early shelters (10000Bc) | Underground structures or caves, vegetal material, rush, palm, etc. | Resource availability and regional factors, society, practical and technical tools, climatic issues, ease of construction and longevity |
| | Early civilization (8000-5500 BC) | Free standing structures from craft based & low tech material: mud brick, stone (mortared rubble) and wood | |
| **Ancient time** | Ancient Egypt, Greek, Romans (3000 BC-1000AD) | Craft based & low tech construction materials, use of the dressed block of stone and concrete in monumental buildings, trabeated and arcuated structure, use of stone columns and arches as structural units, natural colors, domed roof, bronze, copper, iron etc. as facing elements and tools, movable and lightweight furniture | Construction methods, materials and tools, rulers and designer, economy, religion and methodological beliefs, ease of construction and longevity, aesthetic & sensory features |
| **Western civilization** | Gothic, Renaissance, Baroque, etc. (1000AD-1700AD) | Heavy masonry structures, (Stone and brick), flying buttress and pointed arch, Marble stone, braced wood frames, patterning and gilding effect to walls, stained glass window, decorative flooring mosaics, and ceiling with decorative elements, wooden membrane and furniture, craftsman industry, engineered materials, metal (bronze & cast iron) ornaments | Construction methods and materials, client and designer, economy, religion (divine beliefs), styles, aesthetic & sensory features, functional requirements |
| **20$^{th}$ century** | Revival, historicism (End of 19$^{th}$ century)<br>Arts and crafts movement (1860-1925)<br>Art Nouveau style (1888–1905)<br>The Chicago school (1880–1900)<br>De Stijl (1917-1931)<br>International style (1930Art Deco (1920-)<br>-1940)<br>Late Modern (1950-1970)<br>Postmodern era (1972-2000) | Discussed in detail in the table 1 | Technological developments in construction materials and manufacturing methods, design technologies, stylistic approaches and designer, economy, political, social and environmental issues, users' expectations |
| **Present time** | New Modern, High-tech, Digital age design, free form and interactive architecture; Sustainable design Considering eco-tech; nature-oriented design in different levels of sensitivity on ecological principles In parallel there is an inexhaustible range of personal or stylistic tendencies | Concrete and steel frame structure, prefabricated and digital construction methods, free form and shell structures; curtain wall and advanced glazed facade, high performance synthetic and high-tech materials, mass customization, passive and active systems for energy efficient design, environmentally preferable, natural, salvaged, recycled and reclaimed materials, insulated, green and cool roof design, digital manufactured products | Technological advances, environmental concerns and climatic issues, client and designers expectations, styles, digital design tools and fabrication, economy, social & cultural issues, functional requirements |

Note: the table is based on many sources; Gelernter, 1995; Ozay, 1998; Wines, 2000; Wright, 2005; McClure & Bartuska, 2007; Gagg, 2012; Niroumand et al., 2013a; Love, 2013

# Chapter 3

# TOWARDS MATERIAL-AWARE DESIGN

Previously, we have characterized sustainability, technology developments, users and designers' expectations as the main drivers for material-aware building design. At first, this chapter seeks to interpret the concept of material-aware design and then, it will evaluate sustainability, technology, users and designers' expectations considering building material developments. The data emerged from this chapter provides the foundation of next chapter.

## 3.1 Interpretation of the Concept of Material-Aware Building Design

As mentioned earlier, these days we are living in a challenging time of solid matter. Materiality is the major challenge of representation and experimentation of objects. The variety of global choices in building materials and products in one hand, and the environmental and human concerns, as well as the technological escalation on the other hand have created a challenging situation. Therefore, corresponding to this chaotic market of building materials, material developments must be directed to a more futuristic way.

One part of these challenges is related to misuse of building materials that needs to designers' wisely and careful selection of materials considering diverse factors such as environmental, social, economic, functional, and personal tendencies. According to the previous studies in this matter, the possible solution is to have an integrative design approach considering environment, human-society, technology, and economies as the main principles (McClure & Bartuska, 2007). However, some critical questions are still unanswered. It is important to illustrate what kinds of material developments are suited to the future and what are the limitations? Additionally, the role of designers, technology developments, and users must be discussed in detail. These questions have been studied and investigated in this chapter.

This thesis intends to reveal material-aware building design as a comprehensive design framework, and through this achievement, it opens up new possibilities to measure the role and influences of sustainability, technology, users and designers together in selection and development of building materials (Fig.3.1). According to Oxman (2010) who developed the theory of 'Material-based Design Computation', this kind of sensibility on building materials can provide significant solutions to design concerns. She claimed that, "beyond these important historical and cultural considerations, material-based design is strengthening interdisciplinary, collaborative, and research-oriented design" (Oxman, 2010.p.73).

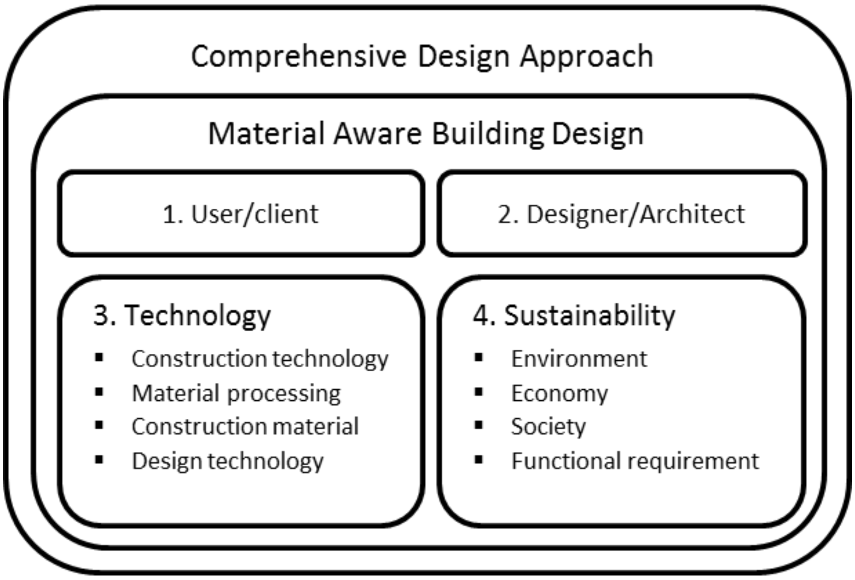


Figure 3.1: Material-aware building design objectives

In the case of material developments, Ashby (2001) asserted that there are five influential drivers for material developments. In this process, market need, design, production, use and disposal are the main backbone, and the new developments are related to science, economics, sustainability and aesthetic branch (Fig. 3.2).

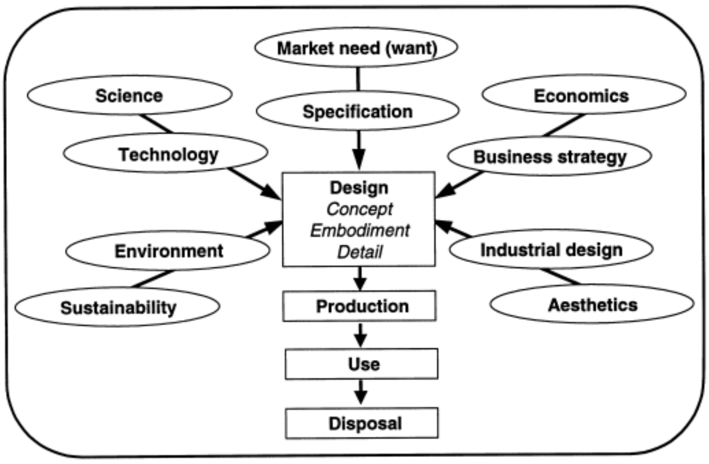



Figure 3.2: Influential drivers for material developments, Source: (Ashby, 2001)

Ashby examined today's situation and influences of each driver for material developments as dominant issues. According to Ashby (2001), the globalization of the material industry and internet trade push the emphasis throw economic, aesthetic and intellectual property of materials. Therefore, the science and technology are creating new materials with technical and aesthetic potentials. In the case of economic and business, viability, market size, investment climate, ease of production and utility justify the new material developments. On the other hand, recently, the environmental concerns have directed the attention on ecological attributes of materials. Accordingly, the environmental load of materials, especially in production, use and disposal stages are the main concerns. In addition, the industrial properties and aesthetic of materials, such as shape, texture, color, and styles influence the desire for selection of material or product by users. Consequently, today’s emphasis is on perceived and multiple attributes of materials (electrical, optical, magnetic, biological etc.). In the recent innovations, the color, texture and sense of surface such as intelligence, transparency, lightness, and elasticity play an important role for the non-structural materials, while the structural materials tend to be designed efficient, lightweight, and standardized (Ashby, 2001; Ashby & Johnson, 2010).

Based on these arguments, this research will examine sustainability, technology, users and designers' expectations as the most influential criteria to achieve a profound evaluation of these items in order to achieve the main goal of material-aware building design. The figure 3.3 shows the hierarchy of material-aware building design considering the initial criteria for material selection and development in this research.

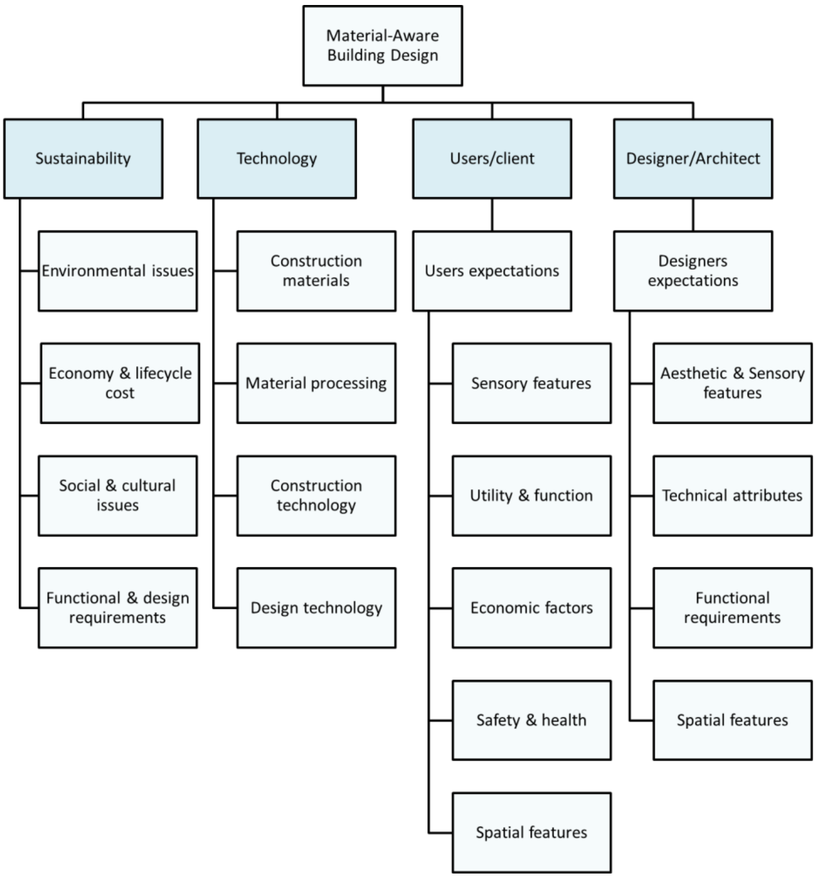



Figure 3.3 Hierarchy of initial criteria for material aware-building design

### 3.1.1 Sustainability in the Realm of Building Materials

After the ecological failures of modernism, during the late 1960s with growing public awareness about environmental issues, such as industrial pollution, resource depletion, and global warming, the architects' urgent effort has become to find a solution to design with a new sensitivity to environmental issues in order to evaluate their designs from an ecological perspective (Wines, 2000).

The early ecological thinkers' emphasis was upon the biological well-being. They consider eco-building design as a system to control building assumption in order to reduce building threats to the natural ecosystem. Through this achievement, the word 'Green' was used for categorizing Eco-friendly buildings or products, and 'Eco-tech' for technological devices in the case of ecological design. Additionally, the bio-climatic challenges sought to evaluate the interaction of building design from the lens of regional climatic issues. In this field, the vernacular climatic practice again has become important and offered chance to prevent from globalization and its challenges by returning to the regionally distinctive architecture (Edwards, 2010). In a further advancement of ecological philosophy, the concept of 'Sustainable design' replaced the 'ecological design' terminology to bridge the social and global economic growth in a long-term policy to the eco-conscious design system (Gissen, 2002). In a general perspective, the environmental benefits, energy and resource efficiency, economy, health and social values are main checklists in sustainable building design approach. Thereby, both humans and the planet could benefit a lot from the positive effects of sustainable building design, which are defined as following items (John et al., 2005):

- Lower green gas emission by using earth-friendly energy and resources
- Reducing energy and resource consumption

• Eliminating pollution by preservation of waste in our natural and built environment

• Increasing the life quality and human health by using non-toxic building materials

• Providing more affordable and desirable living spaces

• Considering long-term policies for economic and social benefits

In order to achieve following benefits, some design methods, rules, techniques and theories are considered as sustainable design principles. According to Chen & Kennedy (2008), the main principles of sustainable building design are categorized as “Respond to place”, “Connection to habitat”, “Conservation of resources”, and “Use of building materials”. Thus, the focus of this research is on sustainability by use of building materials. In this research, for analysis the sustainable performance of building materials in addition to environmental, economic and social aspect, the functional aspect and design requirements is examined. The functional and design requirements of building materials such as flexibility, durability and longevity, ease of construction, maintainability, etc. can be provided with correct selection of materials, and through design strategies for environmental, economic and social benefits.

In the following sections environmental issues, economy and life cycle cost, social and cultural issues, as well as the functional and design requirements as essential factors considering the sustainable performance of building material are profoundly discussed around its sub-criteria. Accordingly, at first, the figure 3.4 gives a general schema of factors for evaluating sustainable performance of building materials in a hierarchy structure.

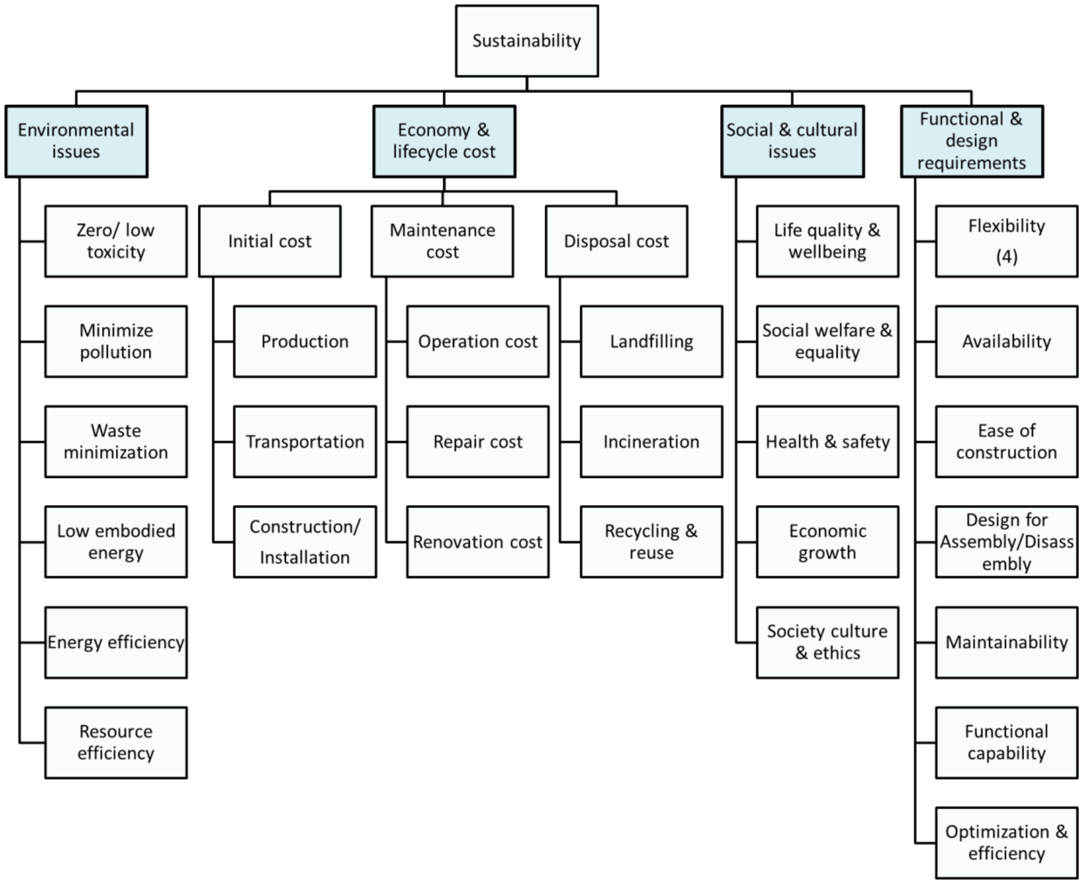



Figure 3.4: Hierarchy of the initial factors for evaluating sustainable performance of building materials (Akadiri et al., 2013; Vakili-Ardebili & Boussabaine, 2010)

#### 3.1.1.1 Environmental Issues

These days, with increasing of world population and needs to further construction, the depletion of raw materials is faster than any time in the history. “During the last century, materials use increased 8-fold and as a result, humanity currently uses almost 60 billion tons (Gt) of materials per year” (Pacheco-Torgal & Librincha, 2013, p.730). Consequently, indulging in mining or harvesting of the raw materials is responsible for soil erosion, as well as ground water and air pollution. Fossil fuel consumption, as power to generate energy of building material manufacturing in the production sector, is responsible for a huge part of greenhouse gas emissions (e.g. carbon dioxide, hydrogen oxides, sulfur dioxide etc.), which increases the process of global warming. Furthermore, the transportation of materials with trunk, trains or boats -by road, rail or sea- accompany with fuel consumption, whilst longer distances cause to greater amount of energy consumption and environmental pollution. On the other hand, the waste of materials such as plastics includes heavy metal and toxins that can be absorbed and destroy the ecosystem as a threat for all species depending on it. The natural and bio-gradable materials, by contrast, safely return to the earth and after composting become a new nutrient for natural ecosystem (Berge, 2009).

In general, dust and particles during the extraction or demolition of building materials, greenhouse gas emission during production, transportation, and construction of building materials, as well as toxic waste additives are the main environmental pollutant factors during material lifecycle (Sharma et al., 2011; Spiegel & Medows, 2010). To avoid these problems, consideration of the performance of building materials in the whole of lifecycle phases, from raw material extraction to manufacturing, transportation to the site, construction, occupancy, and disposal are effective strategies for reducing materials impacts (Fig 3.5) (Sharma et al., 2011).

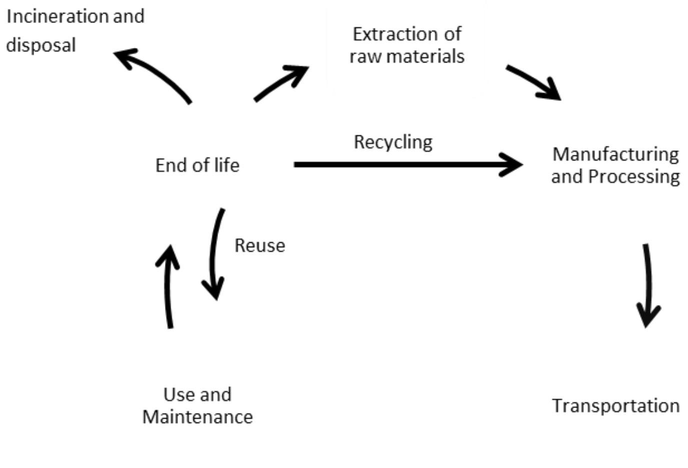



Figure 3.5: Building material life cycle phases. Source: (URL10)

Accordingly, one part of environmental consideration must be on embodied energy by building materials, which encompasses a considerable amount of lifecycle energy consumption (Cabeza et al., 2013). The embodied energy of a product is the energy consumed by extraction, manufacturing, and transportation, until offering the finished product to the market (Berge, 2009). Therefore, using high intensive building materials contribute in the share of the huge amount of energy and increase greenhouse gas emission. The amount of embodied energy of materials varies based on manufacturing process and type, which are presented for common building materials in a pie chart (Fig 3.6). Generally, structural materials represent higher embodied energy. Nevertheless, the emphasis must be on replacing sustainable alternatives for both non-structural and structural materials. As a solution, Zabalza Bribián et al., (2011) suggested that replacing the steel structure with wooden structure, or reinforced concrete with soil blocks could positively decrease the amount of embodied energy from building materials.

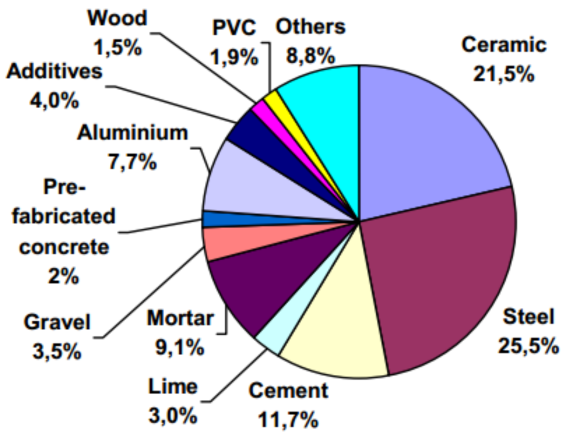



Figure 3.6: Contribution of primary energy demand for manufacturing of materials in the construction of 1 m$^2$. Source: (Zabalza Bribian et al., 2011)

On the other hand, the waste existed at all stages of building material lifecycle from extraction of raw materials, to manufacturing, transportation, construction, use and disposal phases (Spiegel & Medows, 2010). Thus, reduction of wastage and losses during production and consumption is one of the necessary principles. Resource management strategies, for example reusing the off-cut materials in other applications could eliminate the waste in construction phase. Most beneficially, prefabricated construction helps to reduce the waste produced in the construction site, and increases the speed of construction (Berge, 2009). Consequently, material lifecycle thinking and waste management are the best way for reduction of material hazardous impacts on the environment, and indeed, the future of building material development is likely to be based on their lifecycle analysis (LCA) (Pacheco et al., 2012). The designer must consider how much energy and resources is consumed during the whole material lifecycle and what will happen at the end of materials or products lifecycle.

With the rapid progress towards ecological design, the ‘energy’ and ‘resource efficiency’ have received further consideration in this topic. Generally, when considering the environmental impacts of buildings, there is a distribution of energy and material resources, which are closely connected to each other. It is proven that, the operational phase in conventional buildings consumes more amounts of energy rather than the other phases such as material extraction, transportation, or production phase (Mateus et al., 2013). Furthermore, about 80% and 85% of the total energy consumption during building operational stage is allocated to heating, cooling, lighting, etc. (Sharma et al., 2011). Hence, to reduce the environmental loads of use stage, ‘energy efficiency’ strategies should be considered, which are directly influenced by the selection of building materials. The energy consideration in building design is consisting of the combination of external forces such as temperature, wind, and solar radiation with building. In this case, the reaction of building components (both externally and internally) and their ability to filter the passage of light, sound, air, and energy is related to building material performance (John et al., 2005). Hence, the energy efficiency is an integration of building material selection and building component design considering outdoor climatic issues (Sadineni et al., 2011).

In this case, getting benefits from the last environmental technology (Eco-tech design tools), high performance and new developed materials, and passive and active design systems are the main energy efficient categories employed by designers. The uses of natural daylighting and ventilation, as well as energy saving strategies in the design of the building envelope are known as passive design systems (Sadineni et al., 2011). Designing for energy saving encompass designing the whole of building envelope components such as opening (doors and windows), glazing system, roofs, thermal insulation, and thermal mass. Double skin walls, triple glazed window, aerogel glazing, reflective coating, overhang design, and shading devices are passive systems that contribute to the reduction of heat gain and energy consumption for artificial lighting. Moreover, building roof covered with plants (green roof) or earth works as an extra insulation layer and helps to reflection of solar radiation (Pacheco et al., 2012).

As a solution, the environmental study of building materials has opportunities to increase the amount of energy efficiency of buildings through correct selection of materials (Pacheco et al., 2012). Due the fact that most of the energy losses occur through windows, roof and walls, high performance insulation materials provide high levels of energy saving for buildings. As the result of Roufechaei et al. (2013) research on energy efficient parameters in building design, the insulation (for roof, window, wall and floor) by 4.26 value is the most important parameter for energy efficiency. In addition, there are various parameters contributing in energy efficiency, which are ranked in the table 3.

Table 3: The energy efficiency parameters for sustainable development ranked by (Roufechaei et al., 2013)

| Energy efficiency parameters | Mean | Rank |
|---|---|---|
| Insulation (roofs, windows, floors, walls and exterior doors) | 4.52 | 1 |
| Application of lighting choices to save energy | 4.26 | 2 |
| Application of passive solar (take advantage of climate conditions) | 3.98 | 3 |
| Application of natural ventilation | 3.72 | 4 |
| Making clean electricity | 3.51 | 5 |
| Cooling and heating system (environmental friendly materials for HVAC system) | 3.45 | 6 |
| Integrative use of natural lighting (day lighting) with electric lighting system | 3.39 | 7 |
| Optimization building orientation and configuration | 3.32 | 8 |
| Optimization building envelope thermal performance | 3.18 | 9 |
| Use energy efficiency and renewable energy sources | 3.04 | 10 |
| Ample ventilation for pollutant and thermal control | 2.98 | 11 |
| Application of efficient water heating | 2.94 | 12 |
| Application of solar water heater | 2.92 | 13 |
| Application of green roof technology | 2.85 | 14 |
| Use of efficient type of lighting (lighting output and color) | 2.76 | 15 |
| Application of lighting product | 2.71 | 16 |
| Application of thermostats, ducts and metres | 2.63 | 17 |
| Application of artificial lighting | 2.58 | 18 |
| Insulation tank and pipes | 2.46 | 19 |
| Application of ground source heat pump | 2.41 | 20 |
| Demand tank less water heater | 2.39 | 21 |
| Use wooden logs to provide structure and insulation | 2.33 | 22 |

On the other hand, the technological developments in ventilation systems, producing electrical energy and heating, wind-generated power, and rainwater collection system through building envelope design like photovoltaic panels are categorized as active design systems (Sadineni et al., 2011). The photovoltaic panels are categorized as energy-saving materials and components. These crystalline silicon based devices by exposing to direct or even diffused sunlight can generate a low voltaic electric current (Lyons, 2007). Built in Georgia, USA, the RainShine house is designed to maximize the energy efficiency. This two-story house with steel structure gets benefits from natural day lighting and ventilation, energy recovery ventilation, roof mounted photovoltaic system, geothermal heat pumps, and other active and passive techniques. Likewise, the environmentally preferable, high performance, salvaged, recycled and reclaimed materials made it a highly efficient modern house in all seasons (Fig 3.7) (Robert M. Cain architect, 2008). Therefore, designer's knowledge of energy saving technology and materials helps to choose the best passive or active systems for each specific situation to increase the energy efficiency of buildings.


Figure 3.7: The RainShine House by Robert M. Cain architects, Georgia, USA, (2008); Source: (Robert M. Cain architect, 2008)

Nowadays the energy has the larger share rather than building materials from environmental impacts, while, the researchers estimated that in the future because of an increase in building construction, the emphasis is on environmental concerns caused by building material consumption (Van Dijk et al., 2014). Accordingly, in the realm of sustainable building design, ‘resource efficiency’ by sensibility in resource consumption has become increasingly important for environmental impact reduction.

These days, due to consumption of resources faster than their replacement process, the resource management must be considered as one of the requirements towards eco-efficient design. “The records show that building activities are responsible for exploring and consuming about 40% of the natural resources such as stone, sand, wood and water” (Mateus et al., 2013. p. 147). Accordingly, all material resources should be managed according to the benefits of the earth and future generations (Spiegel & Medows, 2010). In extraction of raw materials, the priority must be on renewable materials that can be harvested originally and faster without disruption of the natural ecosystem (Bergman, 2012). Consequently, using from renewable and natural resources such as straw, bamboo and earth materials, or using standards for sourcing wood products is beneficial in conservation of non-renewable resources and resource efficiency (Milutiene et al., 2012). An example of using renewable resources in building construction is Straw Bale Café by Hewitt Studios, which provided a high level of resource and energy efficiency by using form straw bale in the construction of walls (Fig 3.8). The straw bale constructions have good thermal properties, lower price, and lower human health and environmental impact (Milutiene et al., 2012).

Another resource efficiency main goal is to decrease the amount of raw materials and wastage in building construction and disposal phases. Due to this, the concept of reduce, recycle and reuse are considered to support resource efficiency issues. It means to consider elimination in the use of non-biodegradable resources, optimization and simplification, prefabricated materials and waste management by recycling, reusing and re-manufacturing products after their useful life. Accordingly, the strategy of "doing more with less" and getting maximum performance from minimum materials (dematerialization) should be taken into consideration in order to reduce the need for extraction of raw materials (Braungart, et al., 2007; Van Dijk et al., 2014).

Figure 3.8: Straw Bale Café by Hewitt Studios LLP, Herefordshire, UK (2010).
Source: (URL11)

In the recycling process, material will be separated into its main substances in order to represent it again as a raw material. The purity of a material will positively simplify the recycling process, while the wrong method of recycling may lead to more consumption of energy than the production of a new one. Nowadays, most of the current building materials have poor potential of recycling. They are constructed from composite and different hazardous component that are difficult to be separated and recycled. To solve this, material and products should be produced from a "Monomaterial" component that is a homogeneous material like wood, or a mixed material with homogenous nature like glass or concrete (Berge, 2009). Accordingly, providing an index of recyclability of materials makes the material selection process much easier. According to Vefago & Avellaneda (2013) analysis result on recyclability of construction materials, the wooden structure has the highest level of design recyclability (Table 4).

Table 4: Design recyclability for construction materials ranked by Vefago & Avellaneda, (2013)

| Structure | Material | Purpose | Mass (kg/m$^2$) | (%) | Decimal | Hierarchy | Result | Design recyclability |
|---|---|---|---|---|---|---|---|---|
| Concrete | Concrete | Virgin | 416.53 | 88.6 | 0.963 | 0 | 0 | 4.7 |
| | | Infraused | 36.22 | 7.7 | 0.077 | 25 | 1.92 | |
| | Steel | Recycled | 17.41 | 3.7 | 0.037 | 75 | 2.78 | |
| Steel | Concrete | Virgin | 186.29 | 76.1 | 0.761 | 0 | 0 | 18.95 |
| | | Infraused | 16.19 | 6.6 | 0.066 | 25 | 1.65 | |
| | Steel | Reused | 42.38 | 17.3 | 0.173 | 100 | 17.3 | |
| Wood | Wood | Reused | 141.18 | 98.4 | 0.984 | 100 | 98.4 | 98.4 |
| | Resine | Virgin | 2.24 | 1.6 | 0.016 | 0 | 0 | |

More specifically, there are various levels of reproducing or reusing materials. In this case, ‘downcycling’, ‘recycling’ and ‘upcycling’ are different terms that are referred to the recycling process of material and products. Whereas in a downcycling process, one part of material value such as quality, durability or economic value might be lost, in recycling process the material could be used in similar purposes by maintaining its main properties. Subsequently, in upcycling process the material value increases, and material accumulates superiority over the time. Unfortunately, most of the building materials are suffering from downcycling at the end of their useful life (Braungart et al., 2007; Vefago & Avellaneda, 2013). Shigeru Ban designed paper tube structure, manufactured from waste paper products, which is an example of upcycled material. He used this recyclable and reusable structure for building many projects, bridges, and temporal houses for natural disaster victims all around the world (McQuaid, 2006). The IE paper pavilion designed by Shigeru Ban Architects is a temporal exhibition structured by paper tube in Madrid (Fig 3.9).

Figure 3.9: IE Paper Pavilion by Shigeru Ban Architects, Madrid, Spain (2013), Source: (URL12)

Vefago & Avellaneda, (2013) claimed that in the recycling process of materials, at least one change will happen in physical or chemical properties of materials, while in reusing process there is no changes in physical or chemical properties of materials. For more illustration, there is a visual example of wood materials possible recycling destination, according to introduced terms (Fig 3.10).

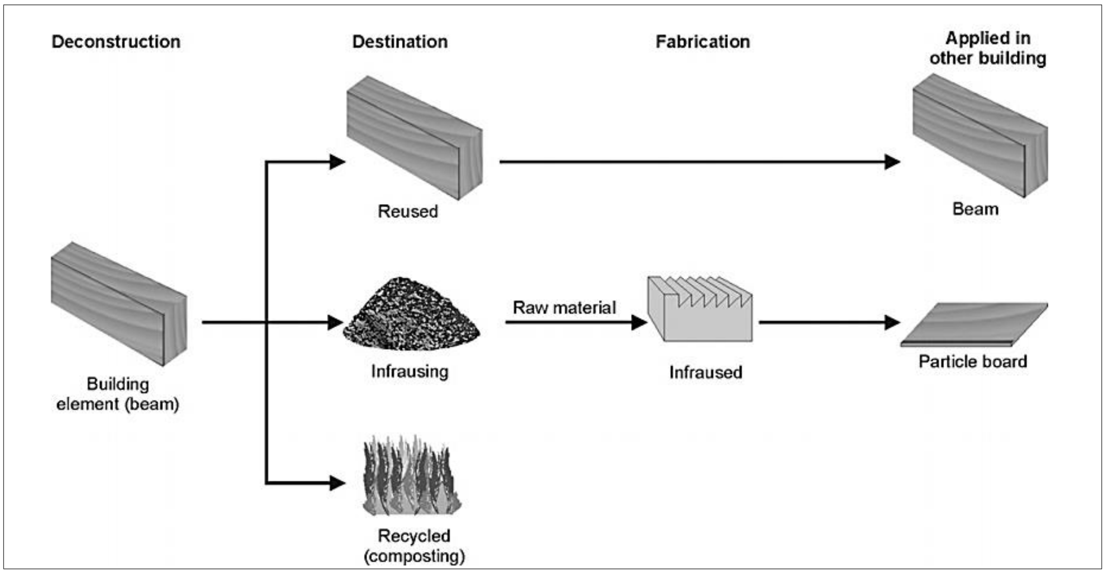



Figure 3.10: Possible recycling destination for wood product, Source: (Vefago & Avellaneda, 2013)

Generally, the concept of reuse and recycle are beneficial in saving energy and resources, reduction of CO2, and waste. According to the hierarchy pyramid of recyclability, reusing is the best option for environmental sustainability, due its need to less energy for preparing the product for a new function (Fig.3.11) (Vefago & Avellaneda, 2013). Therefore, reusing materials must have priority over the others for architects and designers.

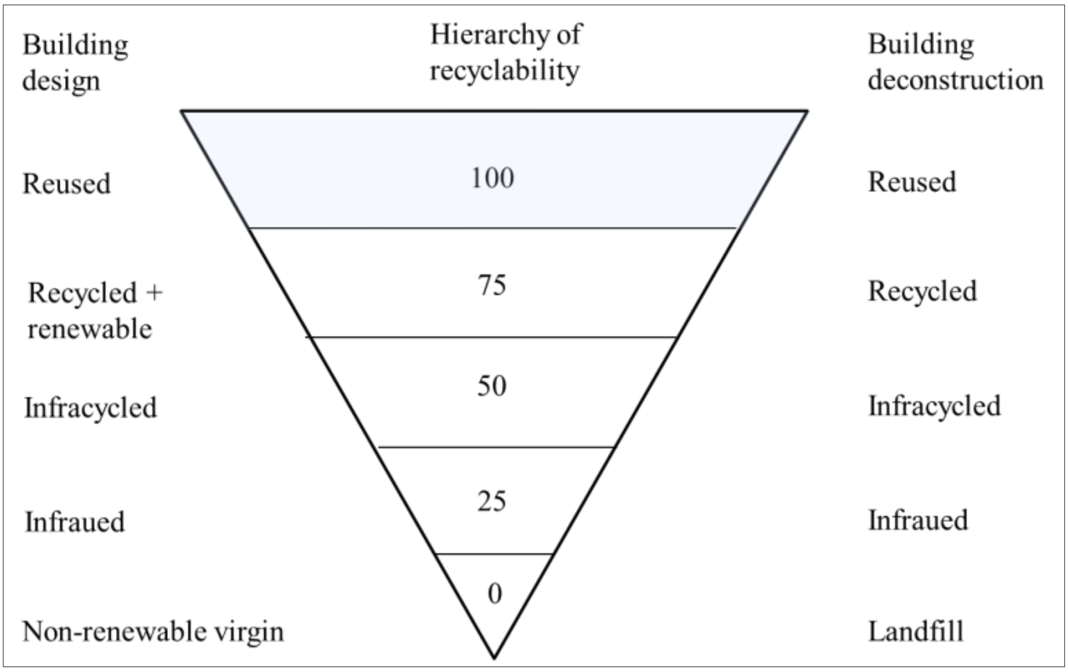



Figure 3.11: Hierarchy pyramid of recyclability, reused as the best option of material end of life cycle for environmental sustainability, Source: (Vefago & Avellaneda, 2013)

Furthermore, prefabricated materials and structures are suitable construction method for reduction in waste and resource efficiency. However, the extensive use of jointing materials is not environmentally favorable and must be considered (Fig.3.12). Besides, considering the efficient packaging of products to the site and use of recyclable packaging materials is important (Bergman, 2012). In this case, glued bamboo prefabricated construction system (GLUBM) is a model of construction system developed by Advanced Architecture Lab that used from renewable materials and prefabricated technology together (Fig.3.13).

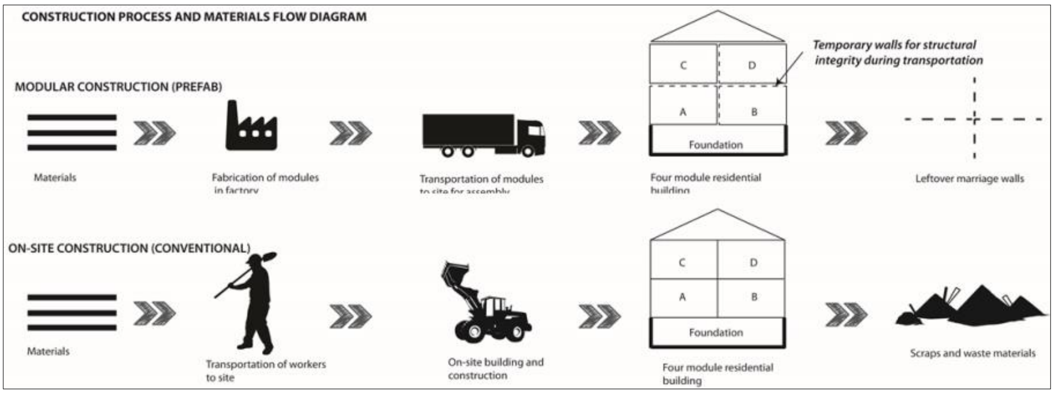



Figure 3.12: Prefabricated construction system and materials cause for reduction in waste and energy efficiency; Source: (URL13)


Figure 3.13: Glued bamboo prefabricated construction system (GLUBM) by Advanced Architecture Lab, Wuhan, China (2012); Source: (URL14)

In general, the eco-efficient strategies by reduction of need for raw materials extraction, waste, and energy consumption during building material life cycle positively decrease the environmental impacts. Aforementioned solutions are arranged in a summary table by the author to provide an ordered organization of data (Table 5). Economy and lifecycle cost is another sustainable challenge for development and selection of building materials that is addressed in the next section.

Table 5: Summary of the solutions for resource and energy efficiency, and pollution reduction considering material lifecycle

| Material Lifecycle | Solutions | | |
|---|---|---|---|
| | Resources | Energy | Pollution |
| **A. Extraction of raw materials** | Use of recycled and renewable resources; careful utilization of natural resources | Minimizing extraction, substitution for non-fossil energy for extraction of raw materials | Choosing materials based on bio-logical resources; considering soil, air and ground water pollution, considering dust and particulates |
| **B. Manufacturing and Processing** | Avoidance of waste and reuse of wastage during production; use from efficient production methods | Using low embodied energy materials | Reduce the use of toxic chemicals, materials that cause larger emission of greenhouse gasses; substitution for non-fossil energy for production |
| **C. Transportation** | Using local resources | Minimize the distance, local materials | Reduction of energy consumption |
| **D. Construction** | Reduce need for amounts of materials; using durable materials; minimizing and managing wastage on site | Considering embodied energy & energy efficiency issues | Reduction of the use of materials; reduction of energy consumption |
| **E. Use and Maintenance** | Flexibility; separated design layouts; design for easy assembly and disassembly; optimize functionality | Using from passive and active design strategies and high performance materials for reducing energy consumption | Avoiding decaying and mold because of toxins and other indoor irritants; avoid materials with harmful and toxic gases, dust or radiation |
| **F. End of life** | Designing for salvage-ability, maximizing recyclability and reusability | Focus on reusing materials | Avoid materials with pollutant particles and chemical substance |

Note: the table is based on many sources; Berge, 2009; Spiegel & Medows, 2010; Milutiene et al., 2012; Sadineni et al., 2011; Bergman, 2012 Pacheco et al., 2012; Cabeza et al., 2013; Mateus et al., 2013; Roufechaei et al. 2013; Vefago & Avellaneda, 2013

#### 3.1.1.2 Economy and Lifecycle Cost

The initial cost of building materials in addition to purchase price involves the cost of manufacturing, transportation and construction. Additionally, the ongoing operational cost, maintenance cost, renovation and repair cost must be concerned. From the benefits of eco-efficient design and passive design strategies, a considerable amount of energy financial cost could be saved. Availability, longevity and adaptability of material service may also help to cost saving (Vakili-Ardebili & Boussabaine, 2010). After the material lifetime, salvage value or disposal cost is another important challenge. According to Spiegel & Medows (2010), it is more cost effective to prevent waste rather than to clear up the land (use less and useless strategy). Therefore, prevention, re-use and recycling are the preferable suggested solution in order to decrease the cost for incineration and disposal of waste through landfill (Van Dijk et al., 2014).

The ecology and economy are inseparable measure in sustainable design. In this case, the first fee paid must be compared with long-term cost saving to evaluate the economic feasibility of a product. The lifecycle cost evaluation helps to estimate the overall cost of alternatives, in order to ensure all performance requirements is achieved through minimum overall cost. For instance, considering the whole of material lifecycle cost helps to examine that a high performance material, however the higher initial cost results in less amount of operational and maintenance cost, which is more economically sustainable rather than other alternatives. Accordingly, in order to analysis the economic factors of building materials, Life-Cycle Cost Analysis (LCCA) methods helps to evaluate all these factors, and offers the best alternatives to choose from (Kubba, 2012).

#### 3.1.1.3 Social & Cultural Issues

In parallel to environmental and economic growth, one part of sustainability benefits is allocated to social and cultural welfare. Our living environment spiritually is shaped by societal values, ethics and traditions. Nowadays, we are facing changes in cultural diversity, which has influenced the diversity of livelihoods, societal values and beliefs. The changes in cultural diversity in one hand, and the problems of population growth, poverty, urbanization, health and wellbeing on the other hand are major concerns in the case of social and cultural sustainability. Hence, this section intended to discuss the influences of materials on people and communities, and the issues that are important in the case of social responsibility.

The main aim of social and cultural sustainability is to improve the condition for living people and future generation. In general, improving human health and safety among workers, consumers and communities, quality of life, happiness and wellbeing, respect for diversity of society, culture and ethics, social welfare and equality through regional society, local communities, and in a global scale are the main goals of social and cultural sustainability (Karana, et al., 2014). In order to fulfill this aim, there is a need for careful planning of the material development process. The social responsibility of building material should be achieved by using local materials, which improves local industry, employment, and leads to economic growth. On the other hand, cultural associations and local identity are important as a part of social and personal wellbeing. Hence, considering cultural and local context are effective in improving human wellbeing (Day, 2003). Furthermore, producing high quality and nontoxic materials considering human health and safety may increase the social responsibility. Accordingly, increased health and wellbeing could be achieved through a detailed analysis of material impact on human health that is examined in detail in the following.

Nowadays, human beings are facing increases of the health problems in their living environment and a considerable amount of these concerns are originating from building materials. According to the World Health Organization famous statement, "health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (WHO, 1946). Hence, we need both psychological fulfillment and biological health, to be referred as a healthy person. To achieve this goal, all risk factors by materials from different aspects should be examined. The first step to investigate the effect of materials on human health is to find relevant facts. The following items are effective factors that influence human biological and psychosocial health (Vural & Balanlı, 2011):

- Visual features: aesthetic, appearance, color and style
- Tactile features: hardness, roughness, heat
- Auditory features: acoustic, noise
- Atmospheric features: indoor air quality, temperature, humidity

On the basis of this, the human responses to the surroundings could be associated with the biological and psychosocial reactions (Day, 2002). The visual and tactile features could cause some problems related to our psychosocial health, while indoor pollutants consist of hazardous emissions from building materials such as the volatile organic compounds (VOCs) causes indoor atmospheric pollution and biological health impact (Green Guide for Health Care, 2007). In order to improve the human health and comfort, all the risk factors by materials in the indoor environment should be examined.

According to aforementioned data, some features related to physics of materials, can affect our psychological and mental health. “Receptors in our nervous system receive sensory information as sensations via the eyes, ears, nose and skin, enhanced by bodily processes such as skin contacts”(Bluyssen, 2009). Hence, the reactions to the visual, tactile and auditory features occur through the human senses. The warmth and softness of the materials could produce tactile welcoming and decrease the stress. For instance, plastic-based furnishings and surfaces like PVC flooring feel cold, and can load occupants with electrostatic charges. The other features such as light, sound, color and smell have effects on mood, and cause the individual fulfillment (Day, 2003). In general, the beautiful places are inherently balanced and by creating the sense of clarity and harmonization, increases the level of satisfaction among individuals. One the other hand, our built environment is placed human social values, traditions, culture, beliefs and memories, and materials are the reminder of these memories and values. Therefore, materials as the substance of our surroundings can nourish our spiritual aspects by cultural associations and social identity that will be discussed further in the later section (Day, 2003).

From the biological perspective, thermal comfort is another common issue, which influences the human health, or noise pollution can cause stress, high blood pressure and cardiovascular health problems. In addition, the lack of hygienic finishes, due to mold and bacteria growth could cause microbial diseases and allergens (Vural & Balanlı, 2011, Fyhri & Aasvang 2010). In the following, ‘Indoor Air Quality (IAQ)’, ‘VOCs as sources of Indoor Air Pollution (IAP)’, and ‘health effects of VOCs emission’ are considered related to the human biological health.

### A. Indoor Air Quality (IAQ)

Humankind spends most of his life inside the buildings, which emphasis the need for a safe and healthy living environment. Accordingly, the investigation of material impacts on indoor air quality and human health is becoming an important issue. Likewise, it needs to search carefully about the materials' atmospheric concerns in the indoor environment. Since 1970, many researchers have been attempting to investigate the nature of indoor air pollutants to improve the indoor air quality (Spengler et al., 2004). In this regard, sources of indoor air pollution and their effects on human health are major concerns related to indoor air quality (IAQ). According to European Commission (1997) "the indoor air pollution (IAP) may consist of a complex mixture of fibers, radon, particles, microbiological agents, allergens, environmental tobacco smoke (ETS), volatile organic compounds (VOCs) and other combustion products". Hence, the indoor air quality can be strongly affected by VOCs off gassing from building materials as one of the sources of IAP.

### B. VOCs as Sources of Indoor Air Pollution (IAP)

There is a wide range of VOCs such as toluene, formaldehyde, benzene, styrene, and other chemical compounds, that can be released into the air and become one of the main indicators of poor indoor air quality (Bernstein et al., 2008). Therefore, the VOCs emissions should be considered as one of the indoor pollutant factors. Emissions of VOCs into the air could be estimated from building material, ventilation system and human activities (Zuraimi et al., 2004 in Shin & Jo, 2012). The whole of indoor materials, floorings, adhesives, furniture and wall coatings could be sources of VOCs emissions, which are harmful to health and well-being of building occupants (Lee et al., 2012). In a more detailed classification, sources of VOCs in our living environments are as follows (Wolkoff, 2012):

• **Building materials:** Paints, insulation, varnishes, adhesives, furniture, wall / floor coverings

• **Home & consumer products:** Personal care products (perfume, spray), cleaning agents, cosmetics, air freshener, pesticides

• **Indoor activities:** Tobacco smoking, cooking, dry cleaning, photocopiers & printers, candles, wood burning

• **Ventilation systems:** Cooling and heating systems, filters, air ducts, kitchen exhaust

• **Biological sources:** Humans, plants, bacteria and molds

Building materials are divided into two categories of dry products, including flooring, wall coverings and insulation foam or etc., and wet products, like paints, sealants and adhesives (Willem & Singer, 2010). Both of these groups could contribute to VOCs emissions. Hence, in the next step health problems caused by materials in the indoor environment, by the investigations of materials' characteristic and their toxic nature are considered.

**C. Health Effects of VOCs Emissions**

This session attempts to analysis negative health effects of volatile organic compounds (VOCs) as one of the main indicators contributing to poor indoor air quality. The toxic emissions from indoor sources could cause short-term or long-term effects on the occupants depend on the levels of exposure to VOCs emissions. According to Ayoko, (2004) the VOCs emissions could cause damage to the mucous membrane in eyes, nose and throat, increasing of allergens, nausea and sensory irritation, as well as more extensive health effects like damages on liver, kidney and increasing cancer risk (Arajia & Shakour, 2013). Therefore, from a biological perspective, evaluation of the negative effects of materials on human health should be considered for both of the long-term and short-term health effects. In a detailed classification by Molhave, the health effects of VOCs can be classified into following concerns (Wolkoff, 2012):

1. Cellular effects (e.g. Cancer)
2. Hypersensitivity and immune effects (e.g. Allergy and asthma)
3. Respiratory effects
4. Cardiovascular impacts
5. Sensory effects (e.g. Irritation and odor)

Furthermore, the indoor air pollution could cause various symptoms and illnesses, mostly referred as sick building syndrome (SBS). Scientists have investigated that, a building can make human, temporarily sick from poor indoor air quality. According to SBS definition, when occupants of a building experience symptom of illness for a short period, but the source of the symptoms are unknown, or the health complaints involve more than one person, it could be defined as sick building syndrome. “All symptoms have been associated with exposure and the problems resolve when afflicted individuals leave the building” (Spengler et al., 2004).

The SBS symptoms include irritation of eyes, nose, and skin, headache, fatigue, and difficulty breathing. Additionally, “the age, occupation, addiction, immune system and existing health problems of building users are significant factors for SBS” (Vural & Balanlı, 2011). The World Health Organization (WHO) listed eight specific symptoms associated with sick building syndrome as follows (Spengler et al., 2004):

• Irritation of eyes, nose and throat
• Dry mucous membranes and skin
• Erythema

- Mental fatigue, headaches
- Airway infections, cough
- Hoarseness of voice, wheezing
- Unspecified hypersensitivity reactions
- Nausea, dizziness

These symptoms identify a building as ‘sick’ and should be evaluated carefully. The result emphasizes the need to further research on the health effects of VOCs on human health. In a general evaluation, the health effects of VOCs emissions from building materials are arranged in a table to provide beneficial information about the emission background of building materials (Table 6).

Achieving a healthy living environment from the architectural points of view needs healthy building materials criteria, to be defined at design stage and then, to be applied in the construction phases (Lee et al., 2012). Since one of provisions to define a product as green is to have low levels of VOCs emissions, the green materials have potentials to improve indoor air quality and human health. In this way, scientists are attempting to devise guidelines and certifications under the label of the green building materials, which carry out a wide range of the indoor and outdoor environmental issues (Willem & Singer, 2010). Therefore, to reduce the health concerns, we need for a healthy living environment made of healthy materials that respect to the human health and well-being.

Table 6: Evaluation of health effects of VOCs emissions from building materials

| No. | VOCs as negative feature | Material type, source of pollution | Health problem | References |
|---|---|---|---|---|
| 1 | Acetic acid (Acid) | Wooden-based products, cork | Short term: Sensory irritation; Long term: chronic bronchitis and respiratory effects | (Wolkoff, 2012) |
| 2 | Benzene (Aromatic hydrocarbons) | Vinyl, PVC and rubber floorings, nylon carpets, carpet with SBR backing, plastics | Long term: Leukemia, Bone marrow damage, cancer Short term: headaches, dizziness, insomnia, nausea, par aesthesia in the hands, feet and fatigue | (WHO, 2010) (Lee et al, 2012) |
| 3 | DEHP, di (2ethylhexyl) phthalate | Plastics (PVC flooring), paints | Long term: Carcinogen and gastrointestinal problems; Short term: Sensory irritation | (Willem & Singer, 2010) |
| 4 | Ethyl benzene (Aromatic hydrocarbons) | Plastics (Polystyrene, latex and non-latex parquet flooring) | Long term: Damage to nervous system, carcinogenic; mutagenic | (Willem & Singer, 2010) (Hess-Kosa, 2002) |
| 5 | Formaldehyde (Aldehydes) | Adhesives, cements, particle board, plywood, paneling, pressed-wood products and vinyl floor tiles, flooring adhesives | Short term: Sensory irritation, coughing, headaches, dizziness, and nausea; Long term: Carcinogenic | (WHO, 2010) |
| 6 | Phenol (Aromatic alcohols) | Plastics, adhesives, (Vinyl/PVC flooring, glue in laminated timber) | Long term: Carcinogenic and mutagenic | (Berge, 2009) |
| 7 | N-Hexane (Aliphatic hydrocarbons) | Plastics (Carpet with SBR backing) | Damage to peripheral and central nervous system | (Spengler et al. 2004) |
| 8 | Styrene (Aromatic hydrocarbons) | Plastics (Polystyrene- carpet with SBR backing) | Long term: Mutagenic; Short term: Sensory irritation | (Berge, 2009) |
| 9 | Toluene (Aromatic hydrocarbons) | Paints, Carpeting polyurethane backing, pressed-wood furnishings, vinyl floor tiles | Irritates mucous membranes; damage the nervous system, Asthma | (Willem & Singer,2010) (Hess-Kosa, 2002) |
| 10 | TXIB (Ester) | Vinyl/PVC flooring | Sensory irritation | (Hess-Kosa, 2002) |
| 11 | Vinyl chloride | Plastics (Vinyl/PVC flooring) | Irritates inhalation routes, Long term: carcinogenic, narcotic | (Berge, 2009) |
| 12 | Xylene (Aromatic hydrocarbons) | Plastics, paints, varnish (Floor oil. Floor wax) carpeting, vinyl floor tiles | Irritates mucous membranes; Long term: damage the heart, liver, kidneys and nervous system, cancer risk | (Hess-Kosa, 2002) |
| 13 | 2-ethylhexanol (Glycol ethers) | PVC flooring, carpet with SBR backing | Damage to central nervous system and cancer risk | (Berge, 2009) |

#### 3.1.1.4 Functional and Design Requirements

Together with the environmental, economic and social issues, functional and design requirements should be considered to achieve sustainability in the realm of building materials. The functional need defines whether a material functions properly for a specific application or not, which through design and material selection provides the benefits of other sustainable principles. The factors such as the materials' physical structure and chemical composition, climatic condition (humidity, rain, wind, etc.), function, as well as its maintenance could affect the life span of materials. Thus, considering the functional capability of materials, and using from long lasting and durable products for a specific function, helping to sustain the material and eliminate the need for raw materials (Berge, 2009). For instance, resistance to wear, break, strike, chemical attach must be considered in the selection of materials in response to users' activities and related to the function of place, while, resistance to moist, humid, fungal attack and other environmental issues must be considered in response to the climatic conditions (Günçe, 1998).

Along with changes in technology and cultural pattern, designers should optimize buildings by designing multi-functional spaces and furniture towards more adaptable and efficient spaces in responding to the future needs. Additionally, an increase in size of the building doubles the amounts of material consumption. Optimization and simplification in building design for structural or nonstructural elements may also reduce the amount of material that is required. For example, a lattice beam needs lesser amounts of materials rather than a solid beam. Hence, designers incorporation of the most lightweight and efficient structure could significantly reduce the need to foundations and overall material usage (Berge, 2009).

On the other hand, another sustainable design requirement for a building is the ability to be adapted to change and flexibility. In general, functional change, adaptability to new utilization, expansion, and mobility are considered as design requirements towards flexible design (Günçe, 1998). Unfortunately, the new constructions have not been designed for easy destruction. The new design solutions, proposed some methods for disassembly and reuse of constructions. To achieve this goal, separated layers for reusing the whole of building or a single component is necessary, and then, each layer must be designed to be easily assembled and disassembled. Accordingly, designing for easy construction and destruction with independent building layers helps to achieve flexibility and adaptability (Bergman, 2012; Berge, 2009). Additionally, buildings need to be adapted to change in usage to several of spatial, technological, and design patterns. According to figure (3.14), the internal partition walls are causing the considerable amount of building environmental impact. Therefore, in order to save materials and energy resources, the emphasis should be on developing flexible building design strategies with lower embodied energy materials (Mateus et al., 2013).

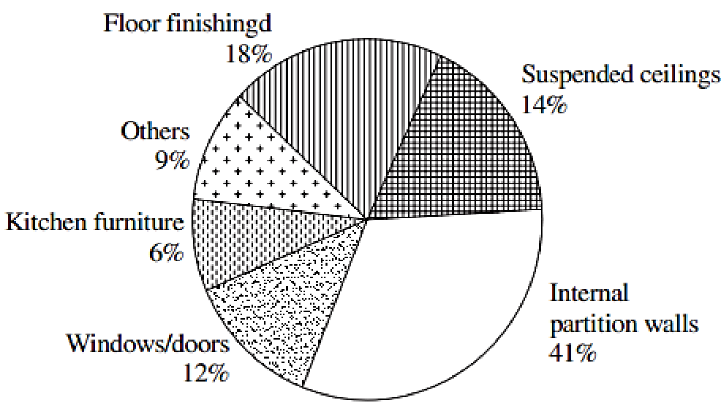



Figure 3.14: Environmental impact of materials used on non-load bearing construction, Source: (Mateus et al., 2013, adapted from Addis & Schouten, 2004)

As suggested by the Mateus et al. (2013), the lightweight partition walls are one of the required strategies. The pros and cons of using lightweight partition walls are as the following:

I. Lower thickness of lightweight partitions maximizes the net floor area.
II. Movability of this kind of partition walls increases the flexibility and adaptability in internal layouts
III. The fibrous materials in the construction of the wall create a better quality of sound absorption.
IV. By use of thermal insulation, the thermal transfer will be improved (Mateus et al., 2013).

In older houses, remodeling the interior layouts of the house needs a huge amount of energy and cost, while flexibility in interior design increases the lifetime of the building and make a building more adaptable. Accordingly, the lightweight partition walls have better sustainability performance than heavy weight partition walls (Mateus et al., 2013). As a result, designers by conscious selection of materials, and considering design requirements, helping to sustain and enhance the function that a material is selected for, and by increasing the lifetime of the building, adaptability, and optimization provide the benefits of environmental, economic, and social sustainability.

#### 3.1.1.5 Contemporary Solutions for Sustainable Building Materials

With increases in pollution of the indoor and outdoor environment, and reduction of resources on a global scale, there is a rapid shift to use of the green building materials to solve aforementioned problems. Last year, INTBAU[1] held a seminar on "The Meaning of Architecture for Communities in Transformation". According to

[1] The International Network for Traditional Building, Architecture and Urbanism (INTBAU), 9 May, 2013, Bedesten, Nicosia, North Cyprus.

Prashad one of the keynote speakers, development of the green materials is necessary for improving the health of communities in transformation, and its application purpose goes beyond the terms like identity, resilience, equity, sufficiency and sustainability. “In general, green building materials should offer five specific benefits to the building’s owner and occupants: (1) Reduced maintenance and replacement costs over the life of the building; (2) Improved occupant health and productivity; (3) Energy conservation; (4) Lower costs associated with changing space configurations; and (5) Greater design flexibility” (Arajia & Shakour, 2013). Using environmental preferable building materials, such as renewable, recyclable, low embodied energy, and locally available materials with minimum pollution and waste should be considered (Mendler & Odell, 2000). Therefore, using the renewable resources such as bamboo, cork, lime, clay, and natural fibers are becoming common alternatives as green finishing materials (Woolley & Kimmins, 2002). For instance, bamboo is known as a green material that grows mostly in Asia; however, long-distance transportation and using formaldehyde as an ingredient do not make it a green favorable choice (Bergman, 2012).

The first step in choosing green products is identifying the green building labeling organizations such as ‘Leadership in Energy and Environmental Design’ (LEED) as one of the famous labeling programs, and then assess the materials according to existing guidelines (Willem & Singer, 2010). Furthermore, there are some certification and testing standards such as, the ‘California Department of Public Health’, and the ‘Green Guide for Health Care’ (GGHC), which offer standards for building materials and products as a helpful guideline for architects who want to select a green material (Willem & Singer, 2010). Unfortunately, most of the certifications and testing programs are associated with high costs and are available just in the US and European countries. Thus, in a local scale, some regulations should be organized to force manufacturers to report the data sheets of their products, in order to increase awareness of architects and clients about the environmental impacts of their products.

On the other hand, because of the complexity of new products and materials, providing a continuing cycle for materials needs to a new lifecycle analysis (LCA) based theory around the concept of recycling and reusing of materials and products. Therefore, William McDonough and Michael Braungart in their book “Cradle to Cradle: Remaking the Way We Make Things” opened up a new way of thinking about the materials and products lifecycle and their end-of-life destination (McDonough & Braungart, 2002). The concept of Cradle-to-Cradle (C2C) tries to redefine the problem, according to nature’s way, and present material production and design in a zero impact and eco-effective manner, in which social, environmental and economic benefits are the main considerations. Moreover, it emphasizes on the need to re-consider, re-invent and re-design the industrial material flow (Branngart et al, 2007).

To fulfill this aim, the C2C defined three rules, such as “waste equals foods”, “use current solar income”, and “celebrate diversity”. This theory introduces two ways of ‘biological’ and ‘technical metabolism’ for materials end of the life cycle. In the ‘biological cycle’ the materials are bio-gradable and can safely return to the nature, while materials belonging to other cycle must be recycled and served as technical nutrients for other products. The plant-based, natural, bio-polymer or other materials that are safe for human and nature are considered as natural nutrient for living system while, the technical continuous cycle uses from high quality mineral and synthetic resources in production that are recovered and remanufactured in a "cyclical" flow (Branngart et al, 2007). This process is called "waste equal food" as a supportive relationship with natural ecosystems, considering long-term economic growth in which there is no waste as the way of nature living organism. Hence, everything must be nutrient for something else and the end-of-life recycling scenario of materials must be designed (Van Dijk et al., 2014). Moreover, C2C proposed that the society must get benefits from solar heat and power of the sun as a renewable power source, and the diversity of culture and place must be celebrated leading to innovation in design. Considering localization of processes and resources are arranged under the title of "Respect diversity" (McDonough & Braungart, 2002).

Based on the Cradle-to-Cradle theory, McDonough and Braungart launched 'The Cradle-to-Cradle Certified Products Program' to evaluate the building materials and products according to their values. The bio-brick is recently certificated biological cement produced by bacteria from abundant waste or natural renewable resources, which grown instead of fired. Thus, unlike conventional bricks, the bio-brick has lower embodied energy and positive environmental attribute (Fig 3.15). Five categories are defined as Cradle-to-Cradle certification criteria such as, material re-utilization, material health, water stewardship, renewable energy and social responsibility, which encompass the basic principles of the theory. The C2C founders criticize the current eco-efficiency method that its focus is just on the eliminating and minimizing the impact and does not follow a long-term goal for solving the problem (Cradle-to-Cradle Products Innovation Institute, 2014). Nonetheless, bringing the whole of the Cradle-to-Cradle principles into practice is not achieved yet and could become a challenge of the future.

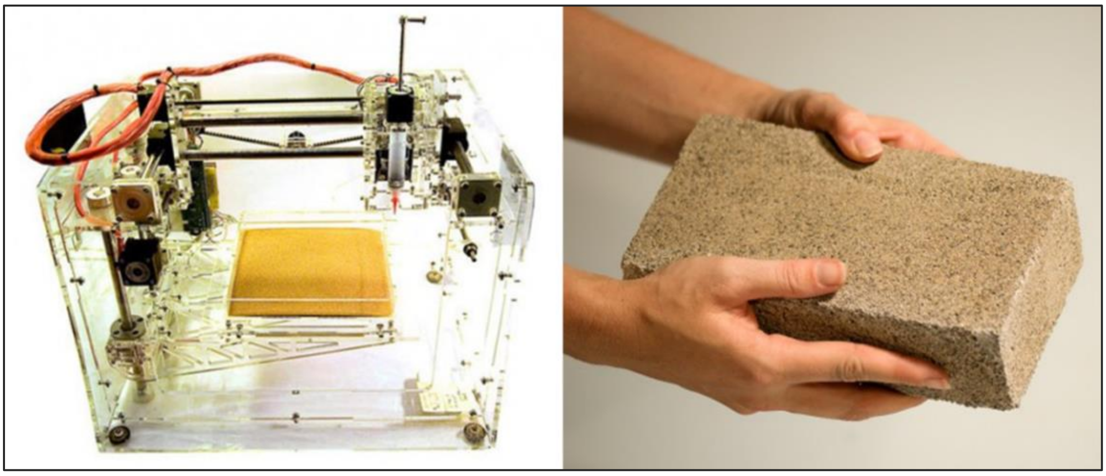


Figure 3.15: Bio-brick: a recently certificated material by cradle-to-cradle institute; Source: (URL15)

### 3.1.2 Technology and Building Material Developments

Since technology is defined as one of the material development drivers, this section provides an evaluation of the innovative building material developments, construction methods, digital modeling and fabrication technologies in the realm of technological possibilities provided in these fields.

These days, there are many new developed technologies that are in queue for providing the ground of their application, and many technologies that their potential application in the case of building materials is not discovered yet. Likewise, the adoption of these technologies in architecture takes longer time than in other industries. Oxman (2010) argued that we are still relying on 19$^{th}$ century technological developments in the realm of building construction materials. This is because architects, as the main decision-maker do not have any overlapping knowledge with these technologies, and then, clients avoid taking risks of investment in unfamiliar technologies (John et al, 2005). Therefore, designers' avoidance to deal with technology developments to direct it according to future needs is one of the major problems. As a solution to the material technology delayed progress, Addington & Schodek (2005) proposed in their book that the gap between knowledge and application must be bridged. Designers must contribute in the technology development process and assess it from different fields rather than just rely on the magical performance of new developed materials to match it to the problem. They must apply these technologies and direct them according to themselves and their clients' expectations. Nonetheless, always there are designers and architects who are pioneers in the implementation of the new technologies that open the way for others to get inspired. However, the gap between material scientific researches and marketing get a long period from the discovery of a material to its availability in the market, which need to a short-term practical knowledge and updating standardizations for new developed building materials.

New materials developments encompasses innovation in the fields of material design (distribution and structuring), processes, and fabrication to achieve specific properties and higher levels of functional, geometrical and aesthetic performance. Additionally, unique properties, intelligent performance, dynamic nature, and self-reliance are possibilities of innovative building materials mostly inspired from biological systems. The incorporation of material science and engineering, together with biology and the assistance of technological solutions are requisites of developing innovative building materials (Ashby & Johnson, 2010). Ritter (2007) claimed that the recent material innovations are mostly allocated to recyclable materials, bio-gradable materials (return to compounds found in the ecosystem), biomaterials, smart materials, engineered materials (hybrid materials, functionally gradient materials), and nanomaterials. Although, the new materials extend design possibilities, the main problems are their cost, availability, and unknown lifecycle impacts. Nonetheless, the introduction of new materials is beneficial in the case that they provide the foundation of the future developments.

In the following sections, bio-inspired materials, engineered and high performance materials, smart materials, and nanotechnology influences on material developments, as well as the role of technology in material design and fabrication are examined to evaluate the behavior of technologically developed construction materials and processes. Prior to this, the hierarchy of initial criteria in the case of technology and material developments provides a general perspective of relevant issues, which later are discussed in the following sections (Fig. 3.16).

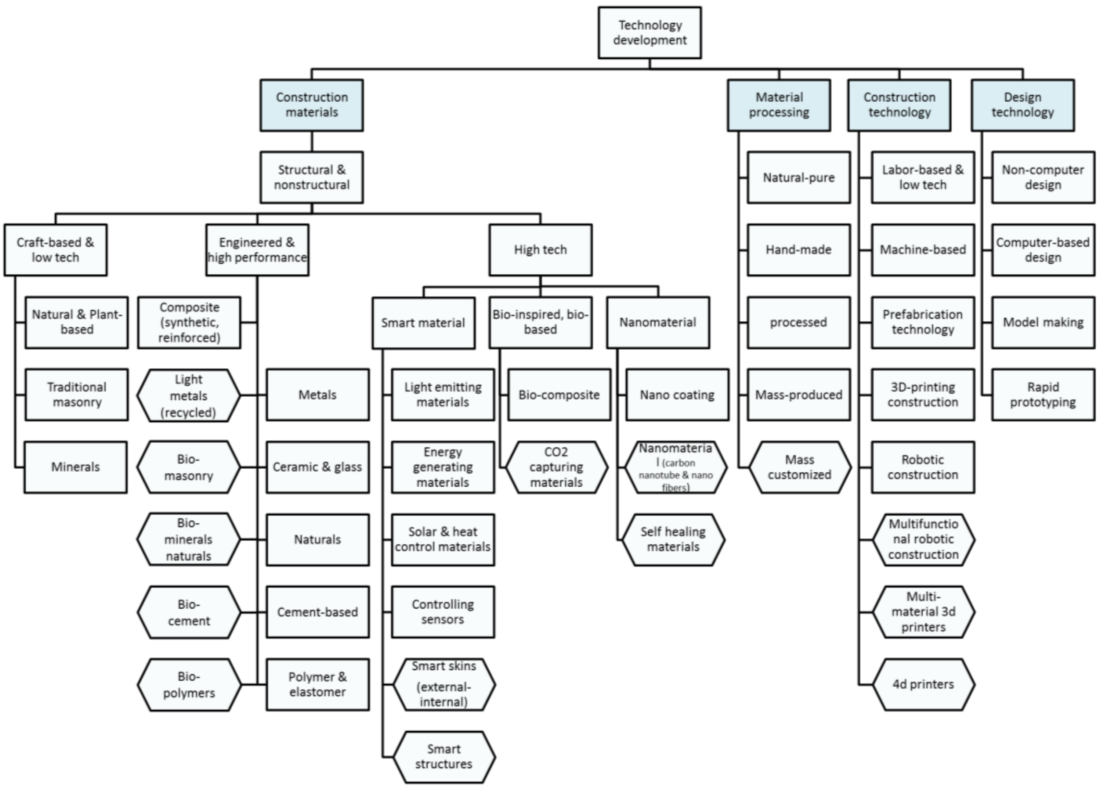



Figure 3.16: Hierarchy of initial criteria in the case of technology and material development (Note: the hexagon shapes are reprehensive of the future possibilities)

#### 3.1.2.1 Biotechnology and Bio-inspired Materials

The nature as the richest source of inspiration in correspondence with science and technology gifted us innovation in material science, and opened possibility for new products and building design. Developing materials by mimicking the ecological systems needs to a deep scientific research in biology and cooperation of advanced technologies (Ashby & Johnson 2010). According to Van Dijk et al. (2014):

> "The study of the formation, structure, or function of biologically produced substances and materials (as enzymes or silk) and biological mechanisms and processes (as protein synthesis or photosynthesis) especially for the purpose of synthesizing similar products by artificial mechanisms which mimic natural ones is referred as the term of biomimetic" (p. 25).

Theorists introduced it as a revolution that unlike the industry, which extract from nature, wants to learn from nature. The mobilization, multi-functionality, lightweight structures, adaptability to change, self-cleaning leaves, self-repairing, self-assembly, cellular growth, fiber structure of wood, honeycomb structures, spider silk and nature process in material production, and thousands of other discovered and undiscovered innovations of nature are considered as a source of inspiration in our built environment (John et al., 2005). Generally, the main effort of 'biomimetic' concept in the case of building materials is to get inspired from the nature's unique way in construction, function, form, processing and producing materials.

Furthermore, optimization, cost effectiveness, and energy efficiency are the sustainable preferences of bio-based materials. Thus, the bio-inspired material and products by perceiving the possibilities of natural ecosystem are truly environmentally friendly and a real green solution. Bio-based materials with the assistance of technology have exceptional performance and are fully biodegradable, while the man-made synthesis compounds do not exist in nature and damaging to the environment (Pacheco-Torgal & Labrincha, 2013). Therefore, today's technological developments, especially in the nano and micro scale design, provided possibilities to consider nature as a model and context for material development and production.

The natural ecosystem is consisting of complex structures with superior mechanical and physical durability, mostly with multifunctional opportunities that may be used in the future of construction materials that are multifunctional, lightweight and high-strength. In this case, the abalone shell is simply a high performance composite material. It is made of calcium carbonate crystal blind with a protein substance that created a composite with a higher level of toughness than calcium carbonate crystals. This bio-composite is a source of inspiration for scientists around the world for its lightweight compost structure. On the other hand, the spider silk is remarkable for its durability and high levels of elasticity. It has higher toughness than Kevlar synthetic fibers and higher strength/mass ratio than steel ratio. Due to this fact, scientists started to manufacture it artificially as a reinforcement agent in supporting textiles (Pacheco-Torgal & Labrincha, 2013).

Thanks to technology advances with the assistance of computer modeling and simulations, the knowledge on biological materials and systems is professionally increased, and led to development in the area of bio-inspired materials. For instance, scientists have been inspired from carbon capturing biological process in production of new carbon sequestering materials. The main philosophy of this technique is to use $CO_2$ in production of materials and to keep it away from the ecosystem (Phur-ghaze, 2013). This technique, by mimicking biological carbon capturing process –as abalone builds its solid shell from carbon dioxide and minerals in seawater- wants to convert $CO_2$ to solid carbonates and use it as construction materials. Tis & Partner

Japanese company developed a kind of $CO_2$ brick from mixture of $CO_2$ and silica instead of its common ingredients. In this method, $CO_2$ is pumped into molds and bonds with silica to make a solid brick stronger than concrete and in a short time (Fig.3.17). The non-structural materials developed by this method are expected to become available in the market in the near future, while its structural applications may be developed in the far future (Phur-ghaze, 2013). As a result, there are useful lessons in the biological systems for building material sector, which are rapidly emerging in building material science and in the future could provide more solutions towards eco-efficient, innovative, and adaptable building materials.

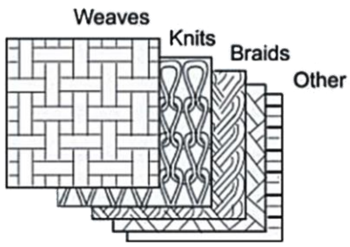
Figure 3.17: The CO2 Sand Bricks developed by Tis & Partner Japanese company, (2011), Source: (URL16)

#### 3.1.2.2 Engineered and High Performance Materials

In parallel to the concerns related to the sustainability issues, having high performance properties such as conductivity, strength, thermal stability and mechanical resistance are essential for material developments. Therefore, material engineers and scientists deal with material properties and composition in molecular scales to fulfill the requirements related to material performance. Scientists attempt to develop innovative materials with new synthetic and composite compounds to achieve unique properties of materials. They seek to optimize selected and specified properties of materials according to its functional requirements and increase the material performance by arranging material properties in macro and micro scale (Ashby, 2013 in Karana et al., 2014). The material properties are 'intrinsic' or 'extrinsic'. The 'intrinsic' properties of materials are related to changes in internal chemical composition or structure of materials, and 'extrinsic' properties relate to macro-scale changes in optical and acoustic properties of materials. The 'intrinsic' and 'extrinsic' properties of materials encompass all of the electrical (conductivity), thermal (heat capacity), chemical (reactivity), mechanical (e.g. toughness, hardness, malleability, elastic modulus, etc.), and optical (e.g. transmissivity, reflectivity, absorptivity) features (Addington & Schodek, 2005).

Fiber reinforced composites, high performance concrete, lightweight metal alloys, polymers, ceramic and glasses, and other engineered materials existing in structural applications, or internal and external nonstructural applications are in this group (Ashby, 2010). The composite materials play a crucial role as one of the families of engineering materials. The composite material is a mixture of two or more reinforcing constituents in macroscopic level (reinforcing element, cores, composite resin and matrix) to achieve improved performance of material in lightness, strength and corrosion resistant (Table 7). It should be considered that, composite components do not dissolve or merge into each other, but acts in harmony together (Ashby & Johnson, 2010; Addington & Schodek, 2005). Moreover, using from plant fibers like cellulose, as reinforcement in composite construction is a positive attempt in development of bio-composite materials (Berge, 2009).

Table 7: Composite structure makes up for increasing the performance, strength and stiffness (Addington & Schodek, 2005)

<table>
<tr><th>Reinforcing element</th><th>Resins and Matrix Materials</th></tr>
<tr><td rowspan="3">Reinforcing materials<br>Glass fibers<br>Polymer fibers<br>▪ Organic (e.g. Kevlar)<br>▪ Nylons, polyesters, etc.<br>Carbon fibers<br>Organization of reinforcing<br>Basic forms<br>▪ Strands, filaments, fibers, yarns (twisted strands), roving (bundled strands)<br>Weaves, braids, knits, other<br>Non-woven matting<br>Films, sheets<br>Other<br><br></td><td>Resin materials<br>Epoxies<br>Polyesters<br>Vinyl<br>Other</td></tr>
<tr><td>Cores</td></tr>
<tr><td>Cores materials<br>Foam<br>Balsa<br>Synthetic fabrics<br>Other<br>Organization of cores<br>Honeycombs<br>Laminates<br>Other</td></tr>
</table>

The material scientists and engineers are continually faced with a need to increase the efficiency and performance of construction materials. As an example, material engineers are trying to change the ingredient and the organism of unsustainable materials like cement to produce low carbon materials. Most of the CO2 released in the cement industry is the result of carbonate calcination. Hence, using low carbon substitute such as slag and fly ash can result in lower levels of CO2 and fuel consumption. For instance, the belite calcium sulfoaluminate ferrite (BCASF) cement has less CO2 gas emission than Portland cement by an equal durability and similar performance. Additionally, replacing the aggregate in concrete by crushing glass or cement with limestone powder, and using byproduct additives to create high volume fly ash concrete (HVFA) are other methods in the concrete industry to reduce its carbon footprint (Phur-ghaze,2013). Therefore, material science and engineering mostly deals with material composition and properties to achieve better synthesis.

### 3.1.2.3 Smart Materials and Intelligent systems

The smart materials are described as "highly engineered materials that respond intelligently to their environment" (Addington & Schodek, 2005, p.1). Unlike the conventional engineered materials that have fixed responses to external stimuli, the smart material systems respond to internal and external energy stimulus with a more specialized and selective approaches in design. These mechanisms affect the internal energy and then alert material molecular and micro structures, and the result will be changes in property of material (intrinsic and extrinsic response) or, the property stays consistent, and energy exchanging from one form to another will be happened. It should be considered that the energy input of smart materials is radioactive, thermal, electrical, mechanical or chemical energy (Addington & Schodek, 2005).

Today, the smart technology is widely utilized firstly for other scientific fields, and then for architectural applications. The NASA and military are pioneers and motivators in the application and development of smart materials. The military wants to employ smart materials for supporting the soldiers, and NASA for aerospace applications. Therefore, designers' attempt must be on developing its suitable applications in the architectural fields. Both two types of property changing and energy exchanging smart materials provide enormous opportunities in architecture. The property-changing mechanism includes phase change materials, color-changing materials, conducting materials (polymers), rheological materials (electro-rheological) shape memory alloys, and liquid crystals. Accordingly, changes will happen in optical, mechanical, chemical, electrical, and thermal properties of materials. In the energy-exchanging mechanism by the transformation of energy in atomic levels from electrical energy to mechanical energy, changes will happen in the physical aspects. The light emitting (electro-luminance), photovoltaic (semi-conductor technology), thermo-electrics and piezoelectric are energy-exchanging materials (Addington & Schodek, 2005).

The phase changing materials (PCM) because of their heat capacity, act as a thermal mass but in much smaller scale. These materials could be a suitable alternative to replace heavy weight and big volume of masonry thermal mass walls (like rammed earth wall) (Zalewski et al., 2012). Using the PCM materials in façade, walls and windows store heat during the day and release it slowly at night. Consequently, the application of phase change materials in gypsum plasterboards, dry wall and façade cladding and many other construction materials is becoming common (Ritter, 2007). Photochromic, thermo-chromic, and electro-chromic are color-changing materials. Photochromic material changes its color by the effect of light, and can be used in finishing materials, paint, wallpaper, glass, plastic and tiles, while, thermo-chromic material changes its color by temperature changes, and can be used in paint, glass, furniture, and accessories (Fig. 3.18).

Figure 3.18: Photochromic tiles and thermo-chromic furniture. Source: (URL17)

On the other hand, the application of smart technology as building component and systems such as façade, energy, lighting, and structural systems lead to an intelligent approach associated with optimization, energy efficiency, and human comfort. For instance, one single material in façade cannot fulfill all functional needs such as thermal insulation, ventilation, light transmission and visual needs. Thereby, the need for a multipurpose material can be achieved with smart technology. The smart materials have direct effects on thermal, luminous and acoustic energy environments. Various light control devices, and glass coatings are introduced, which by changing in angle of view different colors, levels of reflectiveness and transparency are provided. The electro-chromic materials also are examining as switchable filters for solar protection of rooms. They are developed as smart windows to control the color, transparency, and solar absorption by electronic switchable layers. Therefore, by darkening of glass surface, the amount solar transmission and heat passing will be reduced (Fig 3.19). As a result, a smart window provides controlling solar and thermal transmission, thermal absorption, and different levels of view (Addington & Schodek, 2005; Ritter, 2007).

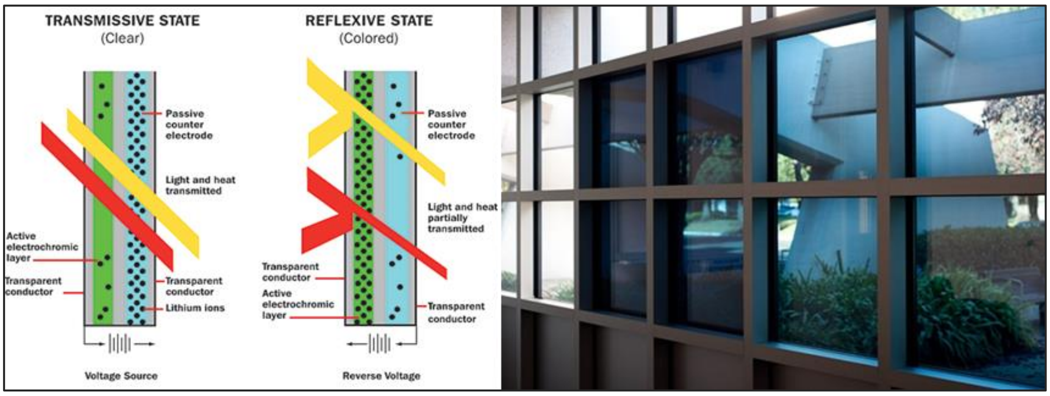


Figure 3.19: Electro-chromic materials for window. Source: (URL18)

Additionally, shape memory materials may contain shape memory alloys, ceramics or polymers. They change their state in response to external forces, like electricity, light, temperature, etc., in a reversible way to their earlier shape. The recovery behavior and deformability are their main advantage (Zhang et al., 2014). Changeable roofs, skins and textiles are its architectural application. An example of shape changing materials is thermo-bimetal sheet that changes its shape in response to the temperature changes. The application of this technology in architecture is inspired from responsive and dynamic nature of human skin that intelligently regulates the human temperature. Therefore, thermo-bimetals are developed as building skin to eliminate the need for air conditioning by responding to environmental stimuli. The case 'Bloom: Building that Breathes' is a research insulation designed by Doris Sung from DO|SU studio architecture. This skin is constructed from two thin laminated layers of thermo-bimetals that by changes in temperature block the air or let it pass (Fig.3.20). This feature can also be designed to respond to the path of the sun and climate. Consequently, this technique has potentials to be used for shape changing, sun shading and self-ventilating skins.

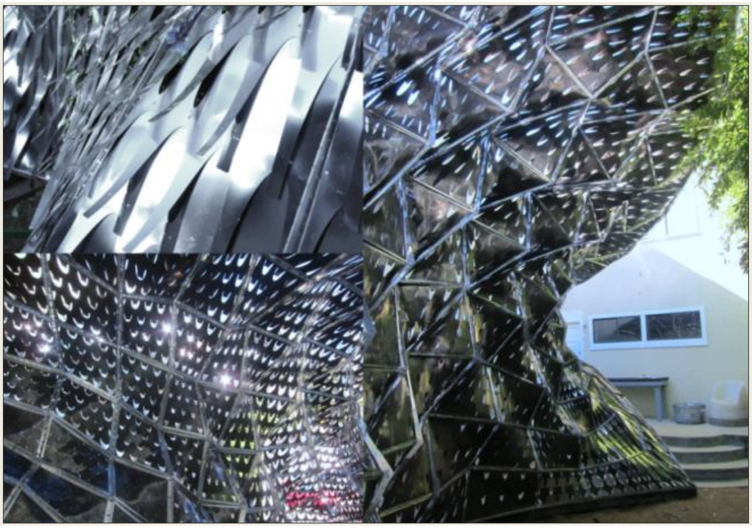


Figure 3.20: Bloom: Building That Breathes, A research insulation by Doris Sung (2011) Source: (URL19)

Furthermore, thermo-electric materials, photovoltaic and piezoelectric materials are grouped as electro generating materials. Photoelectric and photovoltaic cells by absorbing light and converting it into electricity help to optimize artificial lighting system. The silicon as a semiconductor alloy plays an important role in the construction of electro generating materials. Thermo-electric provides electric from temperature differences and vice versa. Thermo-electric thin films can be used as the substrate of the window or membrane in similar function to photovoltaic (Ritter, 2007). Today, Thermo-electric materials due to their relatively high cost and low energy efficiency have not been successful in the market, but in future, they may find their application in building envelope design. Nonetheless, studies show that the combination of these two systems can increase efficiency of the photovoltaic cells (Fisac et al., 2014).

On the other hand, piezoelectric materials provide electricity from deformation (strain) of a mechanical force or vice versa. It means that piezoelectric materials can generate electricity from mechanical pressure and function as an actuator. The architects' scenario from this ability of piezoelectric materials is to use this technology on floors of public spaces, where the footsteps of people can harness the energy. Accordingly, the pressure sensitive piezoelectric tiles on floor of sidewalks, markets, clubs, gyms and other public places are developed with this aim (Fig.3.21). In future, it might lead to systems that can sustain themselves. Additionally, piezoelectric materials in polymer and ceramic types in architecture with sound absorption ability can help to sound reduction (Ritter, 2007).

Figure 3.21: Piezoelectric tiles. Source: (URL20)

Two common examples of light emitting materials are phosphorescence that can be used in wall covering, fabric curtain, carpet and window blinds, and photo-luminescent materials like fluorescence that can be used as a pigment in paint, coatings, cladding, and house accessories. Moreover, light emitting diode (LED) is a familiar material in today's market, which has found various applications in design. Some of light emitting materials like organic light-emitting diodes (OLED) with semi conducting polymer can collect the natural light during the day and serve them as the artificial light at night. This feature of converting and managing solar radiation for night in future may become an energy efficient method for building skins (Ritter, 2007).

Currently, we are faced with an increase in application of monitoring systems in buildings. The smart sensors like motion sensors for home security, structural health monitoring systems, and position sensors are some of the common smart system. The first idea of employing sensor in buildings is inspired by biological sensors of an animal body. The energy-exchanging materials can perform as a converter, sensor for monitoring and sending signals, and as an actuator to get signals and provide an action for the situation. This system is useful to ensure the health and functionality of the building structure. In the future, the advances in micro-electro systems could be increased in the building industry to achieve high adaptable and intelligent environments (John et al., 2005).

At the end, smart materials like other new technologies are faced with some problems and limitations. Some of smart materials contain toxic substances (e.g. Photovoltaic cells) that cause adverse human health effects during manufacturing. Thereby, the emphasis must be on reducing toxic chemicals from these products. Additionally, the lack of market, sensitivity to moisture, low efficiency, high cost, relatively short life, and undiscovered potential are the main barriers for development of smart materials. However, technological solution could break the barriers in a promising foreseeable future to use smart technology for safety and security, sustainability, and convenience.

#### 3.1.2.4 Nanotechnology and Material Developments

The nanotechnology by ability to manipulate the nanostructure of materials (scale of $10^{-9}$ meters) offers a chance to achieve advanced properties of materials. The German Federal Ministry of Education and Research definition of nanotechnology is as follows:

> "Nanotechnology refers to the creation, investigation and application of structures, molecular materials, internal interfaces or surfaces with at least one critical dimension or with manufacturing tolerances of (typically) less than 100 nanometers. The decisive factor is that the very nanoscale of the system components results in new functionalities and properties for improving products or developing new products and applications." (Leydecker, 2008, p. 12)

Therefore, the nanomaterial developments are in correspondence with innovation and incorporation of material science, biology, and nanotechnology. Indeed, once again a promising new technology came from NASA laboratories in the aerospace industry, and military weapons and security applications. Nanotechnology already has found its place in many industries and in the future, its widespread application in architecture and building construction industry is predictable.

In the first place, for any new field of technological development it is necessary to look forward to its advantages and disadvantages from sustainability points of view. It has been proven that, the interaction of nanoparticles with the environment is risk full for both human being and the natural ecosystem. The possible risk associated with nanotechnology is about toxicity of nanoparticles that causes allergic reactions, inflammations, carcinogenic and hereditary effects. The problem is on small-scale of particles, which allow them to transform freely along human organs (Berge, 2009). These problems must be handled and managed by safety regulations and organizations as 'Sustainable Nanotechnology Organization (SNO)' that has recently started its investigation into nanotechnology for safety, health and environment (Sustainable Nanotechnology Organization, 2014).

On the other hand, one of the initial benefits of nanotechnology is keeping the honesty and purity of the materials. This means that thanks to integration of nanofibers and nanoparticles into conventional materials, their characteristics remain untouched, but materials possess new functional properties. Other merits of nanomaterial are reduction in the amount of energy and raw materials used in production, developing highly efficient and lightweight materials, increasing the life span of materials, increasing the performance of materials, reducing pollution by using oxidative catalysis, and reducing maintenance cost by using self-cleaning and easy to clean products (Niroumand et al., 2013b). Therefore, an insight on nanotechnology possibilities and applications in architecture and building material industry help to evaluate the matter from a futuristic perspective, which is necessary especially for architects to get benefits from technological developments.

In the science of nanotechnology, one of the scientific challenges is to control self-assembly molecular structure of materials that allow for bottom-up processing. In bottom-up technique, development starts from smallest size to larger sizes in molecular structure. This process gives higher levels of performance of materials. Carbon nanotube is a deserving example, which its discovery highly influenced the nanotechnology developments. The carbon nanotube has an over plus tensile strength than steel, yet lighter and flexible. It also has high thermal conductivity and acts as conductor, semi-conductor or insulator. Although its manufacturing cost is decreasing, it is still expensive for application in large volume projects. In a promising outlook, it can be used in big structures like skyscrapers and bridges in the future (Niroumand et al., 2013b; Beylerian, & Dent, 2005). Moreover, the transition from the molecular scale to realistic large-scale model also is a big challenge in the development of nanomaterial. Many of intelligent models like self-assembly structures are stopped in experimental and micro-scale applications, and it needs to fusion of material engineering and biology to scale it up (Rosenfield, 2012).

The nanotechnology today's developments are allocated to non-structural, finishing, coatings, texture and insulation materials, however, in future it may encompass a larger area of building constructional materials. Accordingly, scientists are seeking to develop advanced material processing by utilizing nanoparticles. The main blinder of concrete, Portland cement, causes the highest amount of $CO_2$ emission in concrete production. Although, researchers estimated that by 2050 demand for concrete will be increased, in a promising future nanotechnology may provide new solutions for eco-efficiency and higher performance of construction materials. For instance, development of self-healing concrete helps to less cost and environmental impact (Pacheco-Torgal & Labrincha, 2013). Moreover, developments of cellulose nanomaterial and carbon nanotubes could enhance the mechanical properties of materials to create high performance, lighter and thinner materials such as cement-based carbon nanotube composites. Whereas it argued that the nanoparticles cause environmental and health problems, the cellulose based nanoparticles are non-hazardous, and might be a solution to these concerns (Sanchez & Sobolev, 2010; Phur-ghaze, 2013).

Consequently, development of advanced nano-based construction materials with unique thermal, electrical and mechanical properties is not far from reality. Nonetheless, at first, its problem of manufacturing, safety, and cost must be solved (Sanchez & Sobolev, 2010). In a promising outlook to the future, the nanotechnology developments might increase efficiency and performance of both building structural and non-structural materials. At this stage, the use of nanotechnology in finishing materials, mortal, paints, plaster, tiles, and glass provided air purifying, self-cleaning, antibacterial, and other properties that are discussed in the following.

As mentioned earlier, that the source of inspiration for most of the technological developments is the nature itself, the self-cleaning effect of lotus leaves is modeled artificially for material and product industry. The photo-catalysis effect of nanoparticles (titanium dioxide) by the assistance of UV light and water, causes deposited dirt be broken down and be removed from the surface. It is because of the hydrophilic (water-attracting) feature of the surfaces that water runs off from the surface (Leydecker, 2008). Therefore, the application of self-cleaning technology in building cladding, facade and roof, paint, glass and other surfaces are becoming common (Fig.3.22).

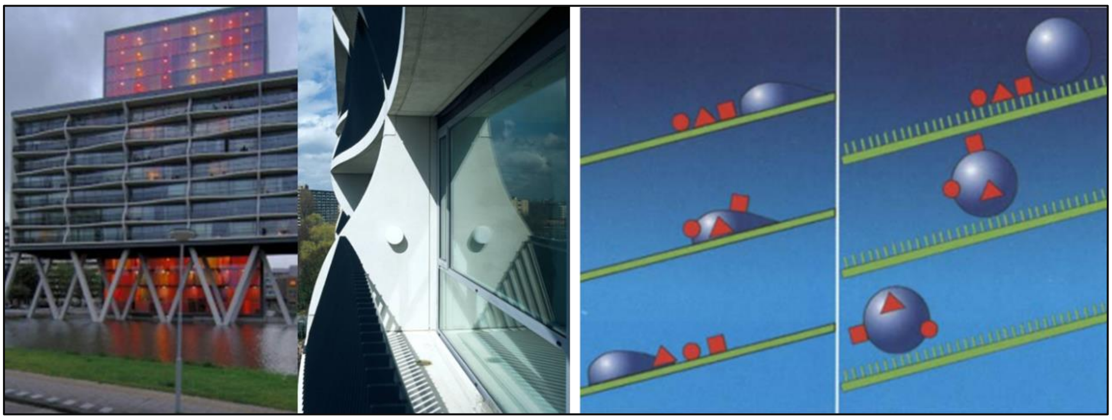


Figure 3.22: Self-Cleaning mechanism in microscopic scale in de Plussenburgh building windows by Arons en Gelauff Architecten, Rotterdam, Netherlands (2006) Source: (URL21, Leydecker, 2008)

On the other hand, because of the hydrophobic effect of nanoparticles (repulsion between water and surface), water runs off from the surface, and dirt is less susceptible to be attracted. Therefore, hydrophobic coating is suitable for ceramics, woods, metal, masonry, concrete and textile surfaces, which help with easy cleaning, saving time and energy. Additionally, a super hydrophilic transparent surface with holes on the surface made of nanoparticles causes for anti-fogging effect, which is a good alternative for bathroom glass or plastics (Leydecker, 2008).

As we discussed previously about the adverse effects of air pollution on human health, the nanotechnology by decomposing the odors into harmless substances enables to reduction of pollution of the air. On the other word, the catalytic effect of nanoparticles cracks and filters the polluting agents. This process is beneficial for elimination of both indoor and outdoor air pollution. Hence, the air purifying materials are widely used in paint and textiles (e.g. Carpets) while, their outside application for construction materials like concrete, paving, roads and facades are under the examination for future developments (Leydecker, 2008).

The basic concept for the self-healing effect of nanomaterials is inspired from the similar function in biological system, e.g. bone self-healing process in the human body. However, the introduction of the material engineering in nanoscale allowed for development of auto-repairing systems for surface coating and construction materials. The self-healing effect involve the use of microcapsules, nanoparticles, hollow tubes and fibers, or microfluidic vascular systems filled with a fluid healing agent diffused in the hosting material. The healing agent by entering of a force, crack or change, will be released and repair it automatically (Aissa et al., 2012). Due to liability of concrete to crack, this technique is highly used in order to repair and maintain the concrete structure. For instance, by mixing the microencapsulated sodium silicate into concrete when small stress cracks appeared, the capsules will burst and release the healing agent (Cilento, 2010). The Figure (3.23) shows an example of self-healing concrete developed by Michelle Pelletier in this method.

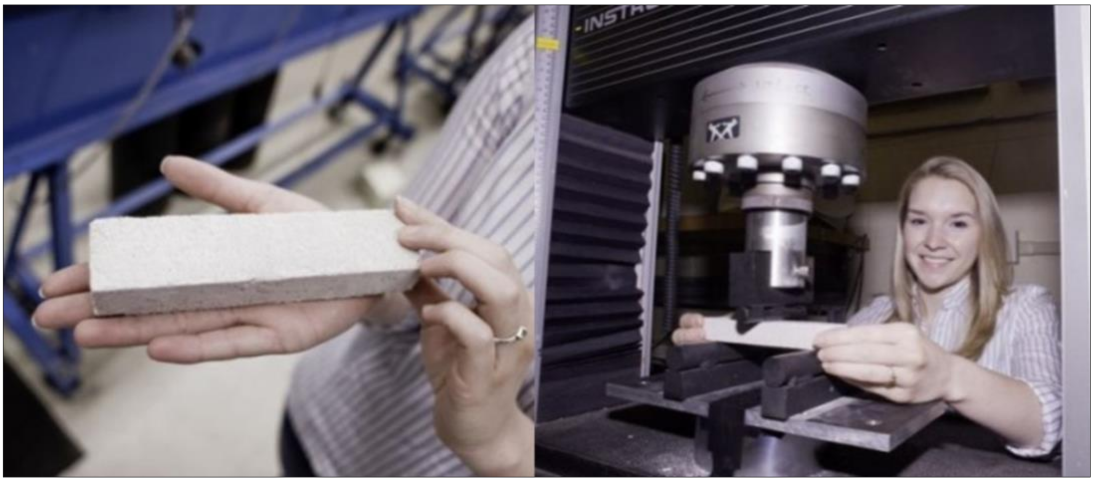


Figure 3.23: Self-healing concrete by Michelle Pelletier (2010), Source: (URL22)

#### 3.1.2.5 Technology through Design, Modeling and Fabrication

In the history of design, many of conceptual ideas just because of the limitations of manufacturing and construction technologies remained unbuilt, while if the current manufacturing technologies were available, they may have been built. For instance, the Leonardo da Vinci's ideas and inventions were ahead of his own time and because of lack of construction technology remained unbuilt. Likewise, recently some innovative designs are conceptualized that still the technology and construction technique for them is not developed. Thus, the aim of this section is to achieve greater understanding of technology through design, modeling and fabrication.

Nowadays, the computer-aided technologies opened new potentials in design technologies so called (CAD) and likewise, it provided new avenues in analysis (CAE) and manufacturing of digitally modeled design (CAM). Thereby, designing complex geometrical forms known as free-form design, their computational analysis, and manufacturing have become possible in the age of digital design and technologies, which were not possible with non-computer design methods, or low-tech production systems. Additionally, the digital modeling systems help to achieve maximum structural performance from minimum materials, which directly affect the energy and resource efficiency, as well as waste reduction (Fernandez, 2004; Oxman, 2006, Oxman, 2010). Thus, developments in materials have been fused with developments in design, modeling and manufacturing systems, which in the future might be completely integrated into one single efficient process.

Accordingly, the integration of CAD modeling and digital fabrication to have a continuous process of conceptualization, materialization, fabrication and construction is the main purpose of digital design fabrication. Rapid prototyping (RP) technology facilitated new potentials for material-construction aspects of design, in which testing prototypes and visualization of models has become possible. It also is influential in showing models to clients to demonstrate design concepts, as Michelangelo used from small-scale physical models to describe the construction technique of his buildings hundreds of years ago. Today, with new fabrication technologies by devices such as laser cutters, micro-mills and additive manufacturing devices, the rapid prototyping small-scale model technologies are available for designers (Sasso & Oxman, 2006).

Furthermore, these fabrication techniques are intended to translate from RP devices to real scale construction known as CNC (computer Numerical Control) devices. The CNC cutting and milling, and 3D printing machine are developed for real scale fabrication and 3D printed constructions (Sasso & Oxman; 2006; Oxman, 2010). For instance, Bram Geenen by programing software to control CNC machine has printed a chair called Gaudi chair from carbon fiber weaves and polyamide rib structure (Fig 3.24). Consequently, the 3D printing is a new construction scenario that in the future may develop low cost and rapid construction.

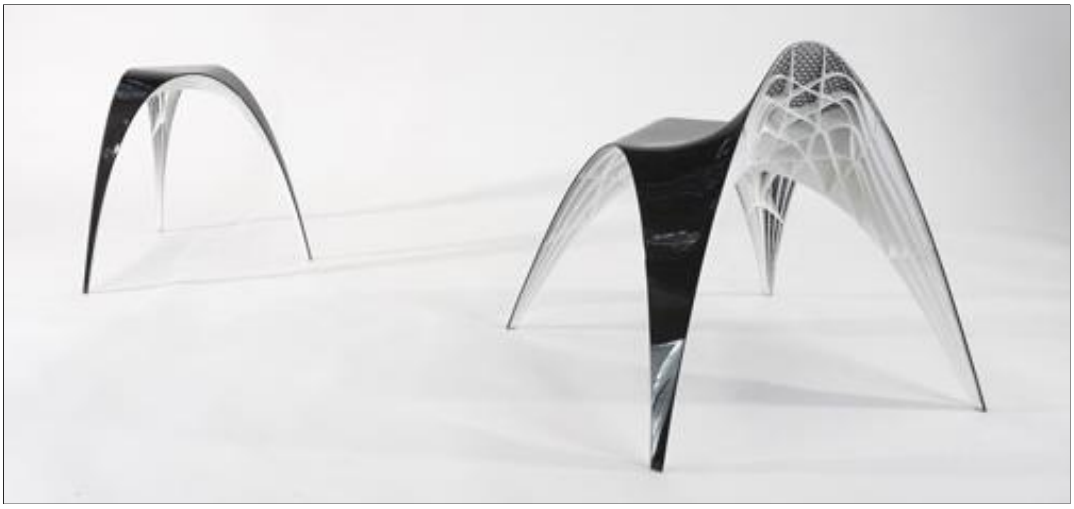


Figure 3.24: 3D printed chair by Bram Geenen (2010), Source: (URL23)

As other advances in the field of material fabrication, Keating & Oxman (2013) proposed robotic fabrication and manufacturing for supporting multifunctional and multi-material processes. They suggested the idea that new manufacturing technologies such as three dimensional printing and multi-axis milling can be integrated with robotic arm to provide a multifunctional robotic fabrication system across spatial scales. However, still there are some limitations for development of this technique; but there is a promising outlook towards customized fabrication of multi-material elements and complex geometries in the larger scales. Researchers of Institute for Computational Design (ICD) together with Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart have developed a robotically constructed pavilion from carbon fiber composite and glass. They used from an innovative robotic construction, computational design tools and simulation method, which led to a high performance, efficient and lightweight structure (Fig 3.25).

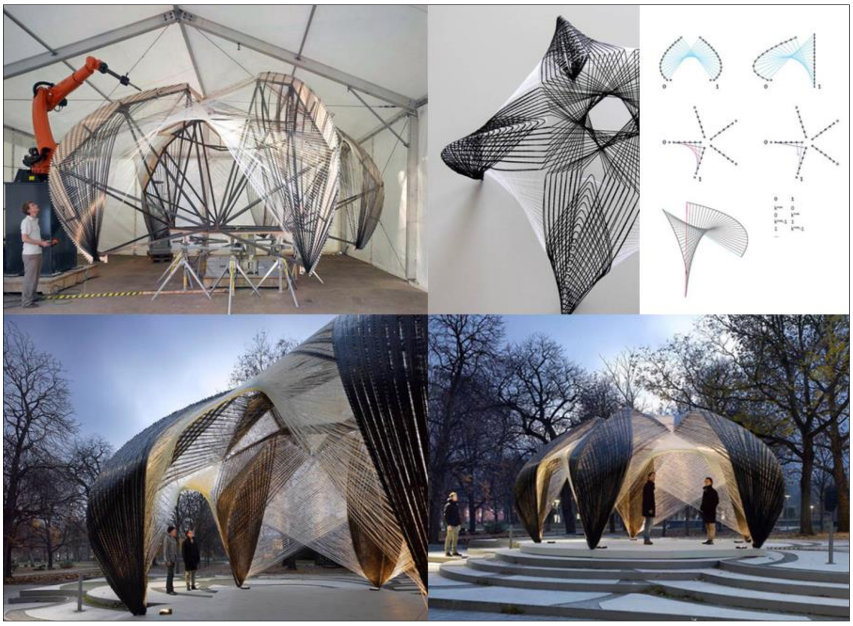


Figure 3.25: Robotically Fabricated Pavilion by researchers of Institute for Computational Design (ICD) and Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart (2012); Source: (URL24)

Materials development for this system also needs to a generative design via modeling. Due to digital device limitations in representing more than one material, there is a need for technology tools to integrate material physical properties for one single material with variable property. As a solution, Oxman (2010) proposed that there is a need for integration of digital design and the knowledge of biology by mimicking the biological systems and fabrication methods. The biological system exhibited design without assembly and moving away from modular industrial design to a heterogeneous design driven by material distribution. She believes that these complex machine assembled systems around us are far from nature's paradigm (Oxman, 2012). Accordingly, she developed a 3D printing system that is capable to print a single structure from variable of materials so called "graded material". By combining digital design and fabrication with biological considerations, Oxman designed Monocoque (single shell) from acrylic composites and utilized from voroni pattern existed in nature. The Monocoque reacts respectably to load and pressure conditions by providing various levels of density, thickness, stiffness and flexibility (Fig 3.26) (Oxman, 2011).

Figure 3.26: The Monocoque (single shell) designed by Neri Oxman, (2007), Museum of Modern Art, NY; Source: (URL25)

On the other hand, combining biologically inspired fabrication, digital technology and material system could lead to sustainable fabrication. In this case, inspired by silkworm ability and with assistance of CNC 3D-axis machine, MIT design lab first applied CNC machine for building the primary structure, then used from silkworms as biological printers to add density to the main structure (Fig 3.27) (MIT Media Lab, 2014).

Consequently, under the ecology tenets and technological developments, the modeling, analysis and fabrication might be integrated into one single process. Creating digital models in both small scale and real world scale, printing different materials in one single system with gradient properties, and mimicking biological manufacturing systems lead to energy and resource efficient fabrication and modeling process without waste, as well as lightweight design with variable mechanical properties, which can be manufactured rapidly.

Figure 3.27: Silk Pavilion: CNC Deposited Silk & Silkworm Construction designed by MIT Media Lab (2013), Source: (URL26)

### 3.1.3 Users' Expectation on Building Material Developments

McClure & Bartuska, (2007) describe our built environment as one part of the world ecosystem, which is consisting of cities, landscape, structures, interiors and products. Materials as physical objects are integrated into each of these categories and in a close interaction with humans. Nowadays, human expects high levels of comfort and life quality within his living environment. More specifically, considering human satisfaction in concept of material-aware design, the notion of users and their experience with materials come into play. This section helps to classify the types of precedence and knowledge, about users' expectations.

Acquiring knowledge of individuals, their needs and expectations is important to designers for a user-centered design approach. This attempt could lead to usable, useful and enjoyable design (Redstrom, 2006). In this regard, users' satisfaction and delight have an important role in the selection and development of materials, which are affected by several of sensory, technical, functional, and spatial features of materials and products (intrinsic and extrinsic properties) (Table 8).

Accordingly, materials or product's attractiveness are achieved through sensory features (aesthetic preferences and styles), however, by the passage of time and changes on society and user's taste, it could change to out-of-date and démodé. Hence, the designers must select adaptable materials to have a longer desirable life. Moreover, usability and utility of the objects by considering suitable selection of materials, which fit between object and user, fulfill the functional requirements of the design. Likewise, the economic viability of material and products obviously has an essential role for its welcoming in the market and its acceptance by users (Ashby & Johnson, 2010).

Table 8: Definition of sensory, technical, functional, and spatial features for building materials (Ashby & Johnson, 2010, Günçe, 1998)

| | | |
|---|---|---|
| Sensory | Visual (color, texture) | Color (warm or cool), textured or pure, transparency (transparent, translucent, opaque), reflectiveness, brightness, smart texture(shape changing, color changing) |
| | Tactile (touch, taste) | Warm or cold, soft or hard , textured or flat, smooth or rough, smart tactile (dynamic, flexible) |
| | Acoustic | Sound absorption capacity, sound transmission capacity, sound insulation capacity |
| | Style | Nostalgic and traditional, Modern and cool, classical and lux |
| Technical | Physical | Material state(Solid, liquid, gas) origin(synthetic, natural), composition (organic, inorganic) structure (crystaline, amorphous) immaterial |
| | Mechanical | Toughness, tensile strength, modulus, hardness, fatigue limits |
| | Chemical | Reactivity, valence, solubility |
| | Thermal | Thermal conductivity, thermal expansion, molding temperature |
| | Electrical | Electrical resistivity (conductor, semi-conductor, non-conductor) , breakdown potential, power factor, dielectric constant |
| Functional | Utility & function | Ease of use, usefulness, functional capability, intelligence, maintainability, fire resistance |
| | Economy | First cost affordability, operation & maintenance cost, longevity |
| | Safety & health | Indoor air quality, hygiene properties( cleanness , bacterial production),physical safety(touch, slip), Nano coating (antibacterial, air purifying, easy to clean) |
| Spatial | Dimensional | Volume (length, height, thickness), weight (light or heavy), size (large and small) smart/dynamic(changeable) |
| | Formal | Shape (regular or plastic), proportion, orientation, smart/dynamic(movable) |
| | Flexibility | Functional change, adaptability to new utilization, expansion, mobility |

On the other hand, considering users in material-aware building design, needs are more basic than demands. Human psychological and physiological needs are variously manifested in their built environment, which is affected by technical, aesthetic, spatial and perceived attributes of materials. The physic of material influences human comfort by hardness, softness, warmth, transparency, color, reflectivity, etc. For instance, the warmth of materials is directly affected by the thermal conductivity of materials, and sound absorption by the modulus and density (Ashby & Johnson, 2010). The human psychological and physiological reactions to color, noise, air quality and temperature are materials unseen influences that previously explained in detail.

The tactile attributes are one of unsolved features of new material developments. For example, from users' point of view, cotton-covered wooden furniture can induce the sense of inviting in a way that plastic or steel ones cannot. As mentioned previously the problem is in the paradox between users' expectations and lifestyle requirements. It is about the solid manner of synthetic materials, while the natural materials are alive and age gracefully over the years. Likewise, the manufactured materials are just approximately like natural ones, while they have not the same smell, feel and personality (Day, 2003; Ashby, 2013 in Karana et al., 2014). The figure 3.28 shows two models of recently constructed chair, one constructed from carbon fiber as a new synthetic material and the other one from fabric and oak wood. Although, with technological advances designer has found ability to create a curve form to induce the sense of smoothness, but it still feels cold and uncomfortable by touch. As other solutions, engineers by texturing surfaces, attempt to give emotions to the surface of materials, or by providing light reflection through material surfaces make it more dynamic, and by changing in material properties give different levels of transparency to the materials (Karana et al., 2014). Consequently, the user has a wide variety of artificial textures to select, but they still cannot provide the familiar personality and warmth of traditional and natural materials. These features are important for users' comfort and satisfaction, especially as internal finishing or furnishing materials and products, which are in close interaction with them. In future, by advances in technical properties of materials, the artificial ones may gain the same personality like the natural ones.

Figure 3.28: From left: Manta chair, made from carbon fiber by Mast Elements (2011), and Chinchero chair, from oak wood and textile by ARumFellow group. Source: (URL27)

Furthermore, the first impression of a space is affected by the way that physical form, space, material, color, light, sound and smells are perceived through the human senses. Mori (2002) defined light, sound, smells and air as the immaterial elements of design that could be placed importantly in the future development of materials. For instance, the smell could make memories alive, imbue richness of material, and provide comfort for users. Therefore, immaterial attributes change the human sense of spaces, and in the future, they may provide dynamic boundaries of space.

This research in addition to quantifiable aspects of building materials considered social and ethical aspects of the material-aware building design. Although, we discussed the benefits of computer-aided design for tangible aspect related to materials, it does not encompass the intangible requirements. During the history, designed objects were evidence of cultural society and provided symbolic meaning by combining of material, design, craft and culture. Hence, the building material-aware design in the realm of material culture is a social practice, which deals with users' cultural differences, values, styles, beliefs, traditions, opinion, and memories.

For example, using from familiar materials increases the sense of place attachment and belonging to different scales of social and individual dimensions, in cities, houses or even a small-scale product (McClure & Bartuska, 2007). These aspects lead to emotional connection of spaces and made the levels of changes in our living habitat slower than other places.

According to previous discussion about influences of technology, there should be a new intersection between users' needs, design and materials, which support the basic requirements of everyday living. User's acceptance of smartness of materials and products in their living environment is affected by usefulness, safety, energy saving, enjoyment, comfort and convenience. Nowadays, the most problem of these materials is lack of concern for humanity, difficulties in application, high cost and short technical life (Chen et al., 2010). These factors could affect human behavior from both personal and social perspectives. Accordingly, the designer needs to interplay between old and new, futuristic and nostalgic, classic and trendy, cheap and expensive, natural and artificial, intelligent and conventional to provide a better interconnection.

In order to achieve the goal of material-aware building design, the selection of materials and its development pattern should be responsive to users' expectations and values by a deep understanding of the physical and psychological needs. Designers must consider a wide variety of sensual, technical, functional and spatial properties in material selection to choose more adaptable, meaningful and nourishing materials. Likewise, they must continually think about connections between users' expectations and lifestyle requirements to gain higher levels of users' satisfaction. According to pervious arguments and referring to the table 8, the hierarchy of initial criteria according to users' expectations from building materials is presented in the below (Fig. 3.29).

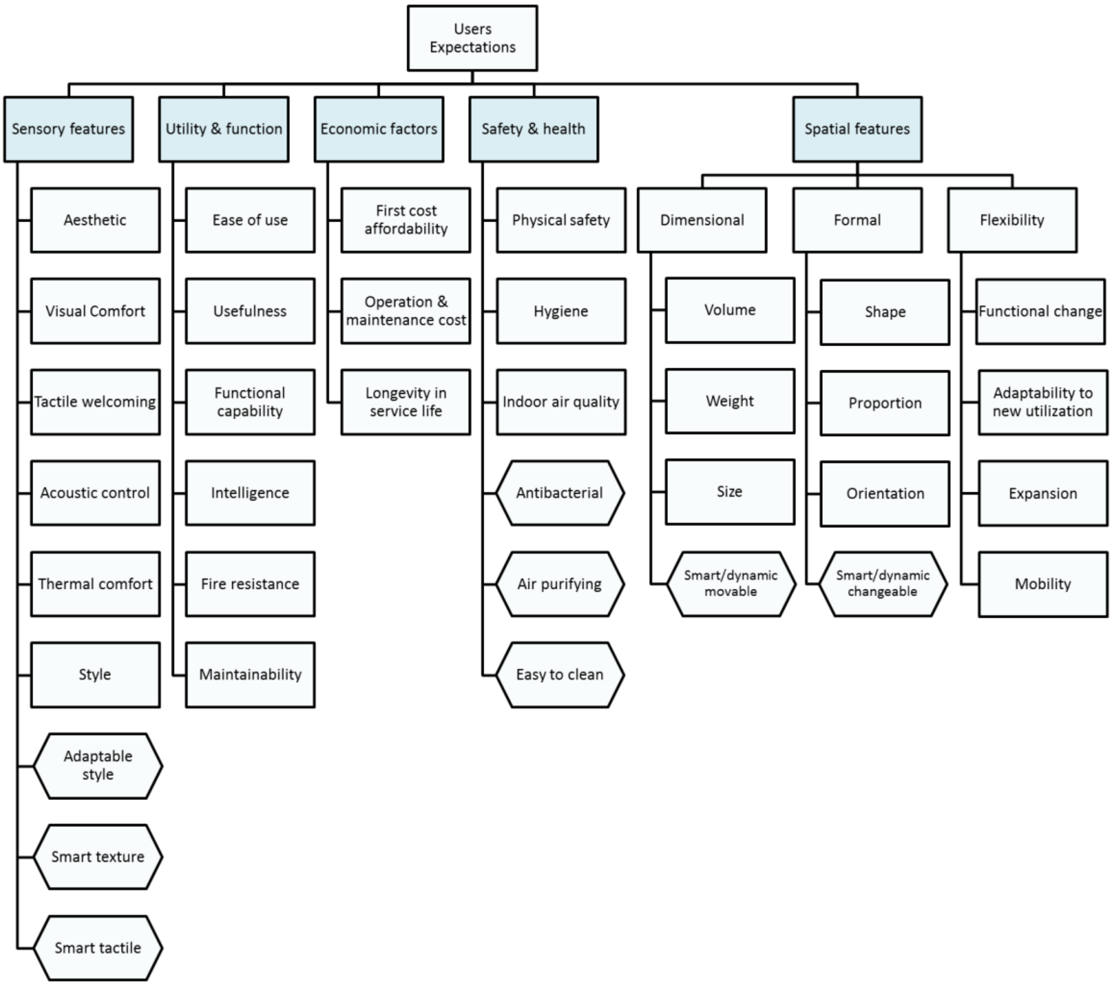



Figure 3.29: Hierarchy of initial criteria according to users' expectations (Note: the hexagon shapes are reprehensive of the future)

### 3.1.4 Designers' Expectation on Building Material Developments

Designers' expectations from material developments may positively encourage the technology developments in the field of material engineering and science towards innovations in the field of building materials. First of all, because the relationship between material and designer is important in the design process, it would be better to evaluate how designer interact with materials and deals with material selection. Additionally, it would be beneficial to gain knowledge about how designers are inspired by artificial and natural materials, new technologies and diverse contexts to create new experiences.

The material selection is the main challenge of designers in the design process. Ashby (2010) claimed that the selection of materials is not separated from the process by which materials are formed, joined and finished. Material processing is influenced by material formability, weld-ability or other relevant properties that are required to make the shape. On the other hand, the function dictates the choice of material and shape. Therefore, these four items are in close interaction with each other, while defining the shape prior to others could limit the selection of materials, and it would be better to start from materials properties and their processes (Fig, 3.30) (Ashby, 2010).

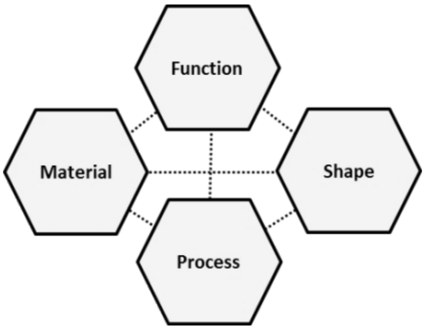



Figure 3.30: The interaction of function, shape, process and material in design.
Source: *(Ashby, 2010)*

Accordingly, designers' knowledge of the behavior of materials helps to get maximum control over the shape and structure. One the other hand, the selected material must be compatible with load forces according to its function. For instance, wood as a structural material because of high tension and bending properties could function as space framing and trusses. From the past up to now, designers were trying to understand and analysis the relationship of material, structure and forces, leading to most structurally efficient designs (Ashby & Johnson, 2010). Based on this argument, design of shapes that use material economically, efficiently and elegantly is a crucial task. Although, the advances of digital design and computational techniques made it easier for designers, still it needs to a deep understanding of material properties. Ashby has prepared material property charts that provide designers beneficial information about the performance and properties of engineering material. Correspondingly, he developed a system for designers that help to an efficient multi-criteria material selection process (Ashby et al., 2004). Therefore, the selection of materials needs an enormous range of tools, knowledge, and multi-objective analysis.

Considering designers' expectation, a questionnaire survey is conducted by Material ConneXion[2] from fifty-four known designers and architects around the world, such as Richard Meier, Zaha Hadid, Karim Rashid etc., about the role of materials in their design, and how materials inspire them, or if the selection of materials has any specific visual, cultural, textural, and other considerations for them. For this purpose, four written non-structured and open-ended questions are designed as the follow (Beylerian & Dent, 2005):

1. *Tell us anything you want about how materials inspire you, any ideas, wishes, provocative statement in regard to materials.*
2. *What is the role of innovation in materials or manufacturing processes in your work?*
3. *What is your favorite material? Where do you see the most potential?*
4. *What would be your dream material? What properties would it have?*

[2] Material ConneXion is a global source of new and innovative materials for architects, artists and designers. This library is founded to provide thousands material samples for diverse industries. Source: *[http://www.materialconnexion.com/]*

In this research, the author categorized the answers to find a realistic insight of designers' expectations from materials' developments. Additionally, designers' futuristic imagination is a good source for planning the basis of the future developments. The evaluation of data, leads us to achieve the influential factors for future developments of material from the designers' point of view. Based on the questionnaire responses 'aesthetic & sensory features', 'technical attributes', 'spatial feature', 'smartness & intelligence', economic factors', 'environmental factors' and 'functional capability' are the major issues considered by designers. According to the responses, the pie chart shows the statistic results and the percentages refer to the number of responses for each criterion (Fig 3.31).

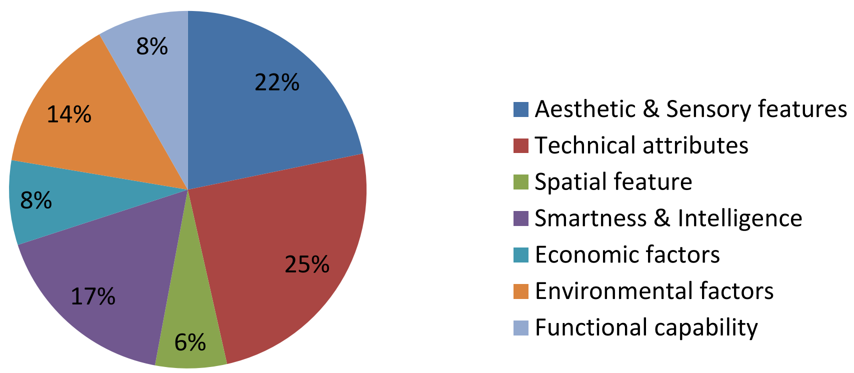



Figure 3.31: Designers' expectations from building material developments, according to questionnaire survey retrieved from material ConneXion (Beylerian & Dent, 2005)

As the result shows, about 25% of responses are allocated to 'technical attributes' which defines its high levels of priority for designers. The technical attributes of materials have previously been identified in the table 8. The 'aesthetic & sensory features', 'smartness & intelligence', 'environmental factors', 'economic factors', 'functional capability' and 'Spatial feature' are the other expectations that organized according to their levels of importance for surveyed designers. It should be considered that the results are general and the amount of importance of each criterion would be changeable in each period. In addition, the answers are gathered from a small group of designer and there would be more detailed expectations that are not mentioned here. Nonetheless, the results are beneficial as provide a basic knowledge of the designers' expectation helping to develop its hierarchy structure. Based on the pie chart results (fig.3.31), figure 3.32 shows the hierarchy of initial criteria for designers' expectations from building material developments.

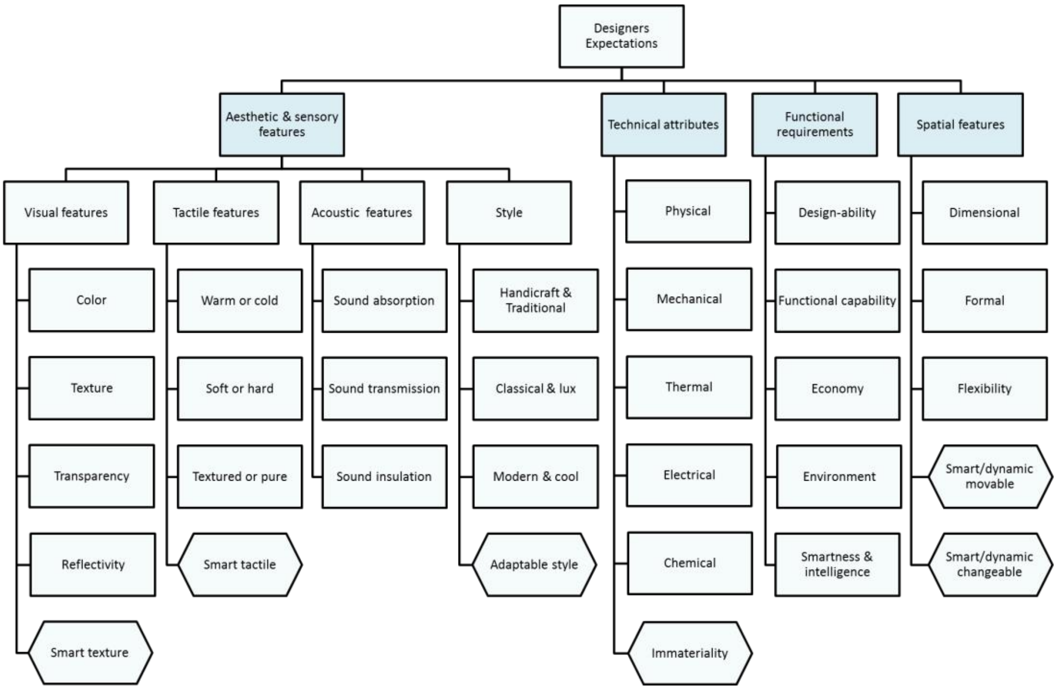



Figure 3.32: Hierarchy of initial criteria according to designers' expectations (Note: the hexagon shapes are reprehensive of the future)

To sum up, the most of surveyed designers have a positive attitude towards new materials and technologies as a source of innovation in their designs. Their dream material has multiple and perfect properties integrated into one material. A super material that never gets dirty, it is intelligent and responsive to external stimuli, something transformative, programmable and changeable in diverse patterns, colors and transparency. It must be formable, long lasting, multifunctional, and with structural features for both internal and external applications. Some of them are searching for something seamless, lightweight and immaterial. For others, sustainability, dematerialization and recyclability have priority for future developments. On the other hand, most of them are fascinated by multiple characterizations of polymers, and wishing for a recyclable and biodegradable one for the future (Beylerian & Dent, 2005).

### 3.1.5 General Conclusion of This Chapter

Because the building material industry is integrated across diverse sciences, material-aware building design provides a comprehensive approach considering ecological, social, cultural, technological and economic aspects based on methodology of the research. Therefore, this chapter has provided a detailed evaluation of sustainability issues, technology developments, users and designers' expectations in the realm of material design and developments. From the data presented in this section, it can be concluded that these four criteria are in a close interaction with each other. For instance, resource and energy efficiency strategies provide the benefits of the human, society, environment and economy. Furthermore, the Green and Cradle-to-Cradle certificated building materials are described as contemporary solutions that try to evaluate building materials from environmental, social, and economic perspective to introduce the best alternatives.

Considering ‘technology and building material developments’, the interaction of the science of biology hand in hand with technology developments in material engineering at the macro and micro scales have enabled valuable lessons and unique solutions for material developments. Likewise digital design, modeling and manufacturing have motivated efficient fabrication of new forms and materials.

In addition to engineering, the properties of materials, and environmental issues, it is crucial to achieve users' satisfaction. Thus, the next section was allocated to material development from users' point of view considering users' expectations, values, and psychological and physiological needs. The objectives of this section would be achieved by considering the material sensory, technical, spatial, and functional attributes, as well as intangible factors such as culture, traditions, beliefs and other social and personal values in the material developments. On the other hand, designers have an important role in material selection process and directing the future of material development. As the results of evaluation of the designers' responses to a questionnaire survey, the basic data for designing the hierarchy of their expectations from material developments has provided. In general, for architects designing with people considering human behavior, culture and user participation, as well as designing with technology for collaborative and creative design, and sustainability considering energy and resources are other important dimensions of material-aware design.

Finally, all the collected data this chapter will be used as the essential knowledge for the evaluation of material developments in the chapter 4. To sum up, it can be stated that the concept of material-aware building design encompasses comprehensive principles in the selection and design of building materials considering the future needs. The knowledge of users and materials, market needs, economy, technology advances, and environmental considerations are effective motivators in conscious selection of building materials. The material-aware building design principles and methods are shown in a schematic perspective in figure 3.33. As a result, now and in the future, material-aware building design methods must be considered towards a more sustainable world.

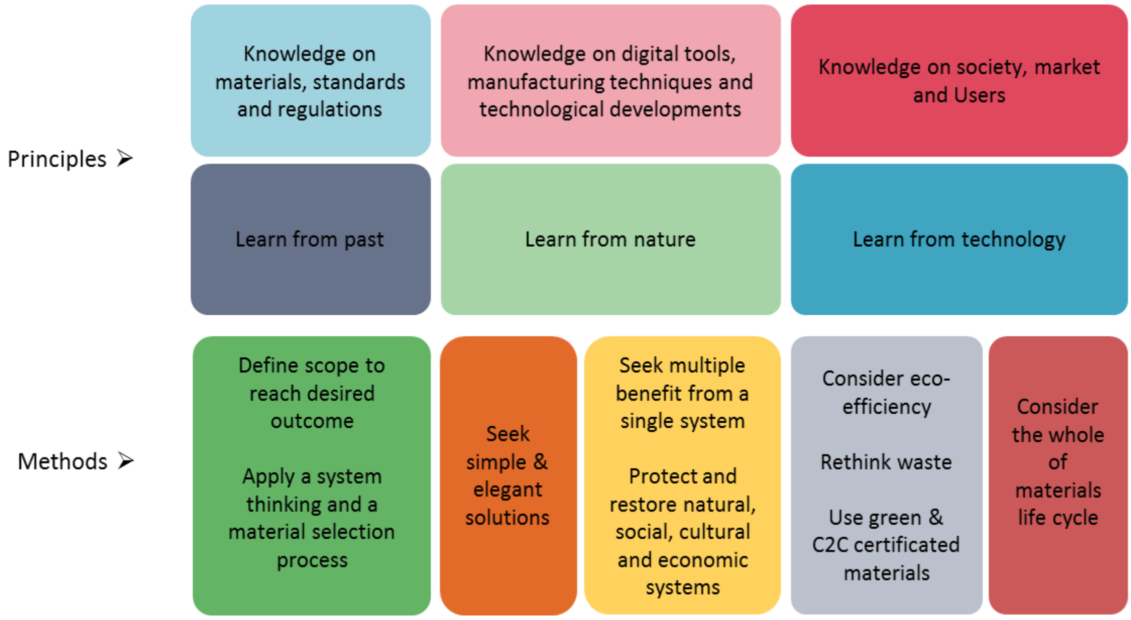



Figure 3.33: Principles and methods of material-aware building design

# Chapter 4

# EVALUATION OF BUILDING MATERIAL DEVELOPMENTS FOR THE FUTURE

This chapter aimed to go further, according to all examined data about the influences of sustainability, technology, users and designers' expectations from the past to the present to foresee the future of building material developments. Through this achievement, a general perspective and the main target for material scientists and designers will be provided. Previously, many thinkers tried to envision diverse versions of the future developments, or some of designers' futuristic perceptions opened the way for future development. In this way, forward-looking movies, innovations in prototype scale and even the futuristic minds are creating versions of the future in our surroundings. This research is going to touch the important developments that are possible for the future of building materials by proving them with support of the pervious developments in the history of the building materials.

## 4.1 Theoretical Analysis of Building Material Developments

With turning back to the history, development in construction tools, quarrying industry, industrial revolution, world wars, and environmental crisis, all speeded or postponed the predictable progress in building materials developments. Sometimes, technology available for other sciences becomes a motivator for designers. For example, as explained previously, some of the aerospace and army technologies have found their applications in building material industry and speeded its development. On the other hand, due to environmental crisis, thinkers argue that a change must be happening on methods that industrial revolution provided for us, considering the way that we are producing and constructing materials. Therefore, the contemporary attempt at changing the current situation is about respecting on human beings and the environment for a sustainable future. Coming back to the locally available, traditional and clay-based materials, development of green building materials, the progress in science of bio-based material, learning from the nature metabolism and early vernacular buildings, Cradle-to-Cradle concept, or other described attempts try to postpone or change the direction of technology developments in a more sustainable way. Thus, technology development comes of the age and in response to the specific time requirements, as it always happened through the history. As a result, in the future also, the building materials are likely to continue their progress while, technological, cultural, social, political, economic and environmental forces could change the direction.

The role of technology in future developments and its interaction with human being would be one of the challenges. As discussed previously, artificial, synthesis, intelligent, and other new innovative materials are rapidly developing due to the living requirements; however, it can be predicted that in future also the human values and behavior are the main obstacles to extra changes in the human living environment. Hence, it is not far from mind that the historical roots, craft-based aesthetic, ethical and cultural values, as well as stylistic approaches continue as the source of the future symbolism. Generally, the new technologies bring advances, comfort, forward-looking attitude, and even some concerns with themselves. According to pervious discussions, it is clear that to achieve material-aware building design, matching the available, user-based and functional technology with a minimum environmental footprint is crucial. As a result, the technology phenomena through correct use of materials can lead to ecological and adaptable design in the future. For instance, the nanotechnology, by ability to keep the honesty of materials, while increasing the performance of materials may become a sustainable technology in the future, if its relevant concerns to be completely solved.

The dramatic increase in world population is providing an increased demand for material consumption and construction that speeded the process of global warming, resource and energy depletion, and other environmental challenges. And, indeed today is the time to think about future concerns, possibilities and developments. It has been estimated that by 2050, the world population would be about 9 billion people and 75% of this population may live in cities, which would result in an exaggerated concern for sustainability issues in the future (Rackard, 2013). Consequently, due to the importance of energy and resource efficient design, the technology should continue its assistance in providing self-efficient buildings. The building skins by the ability of smart materials may act intelligently to environmental stimuli to provide users' comfort. Façade skins may absorb heat within daylight and release it at nights, control the amount of absorption of light, save and produce its required energy, and act as an air-conditioner. In addition, nano-based materials might help to filter the air from pollution and provide advanced solar absorbers. The photovoltaic materials also could be embedded into building skin for aesthetic and efficient results. Therefore, it is not far from mind that all of these functions integrate into one single skin with multiple properties and self-supporting ability to increase the efficiency and aesthetic requirements of buildings.

During the industrial revolution, concrete and steel mass production with assistance of new fabrication methods changed the design thinking of architects. In the future also, it is expected that similar revolutions in new materials and fabrication techniques may influence design and construction process. It can be noticed that from the past up to now, new developed materials such as burnt brick, glass and steel, at first due to lack of production technology were expensive and had limited applications, while later with the economic growth and invention of new production methods, they have been mass produced. This might be a prospect for innovative materials and technologies such as nanotechnology or smart materials, which are rapidly passing their revolutionary process to be accepted by society, become affordable, and find their place on the market. In the future, due to the importance of resource efficiency, the recycling and recyclability of construction materials should be given priority over other features. The bio-composite materials, especially bio-polymer, bio-concrete, and carbon capturing materials may move from scientists' laboratories to large scale production to replace the production of conventional cement-based and other unsustainable construction materials (Phur-ghaze, 2013). The artificial but bio-based materials reinforced with natural fibers and with high strength and lightweight structure could replace the other conventional or natural materials utilization. With needs for resource efficient strategies, most of composite materials are designed to have recycled content like crushed stone tiles with bio-based resins, rather than solid stone blocks. Wooden materials also have one hundred percent recycled content that are laminated and highly pressured to achieve enough strength.

The structural materials in the past were massive and heavy weight elements in order to respond to the load. Gradually, the need to wider spans and high-rise buildings have improved structural elements to become thinner and lighter, while with higher capability to tolerate the load. Indeed, in the future also due to lack of living space, the need for efficient, lightweight and high performance structures will lead to progress in structural materials. Additionally, the use of self-healing technology and sensors for monitoring damage may increase the lifetime of structural materials. On the other hand, the dream of integration of building skin and structure could become true. Development of carbon nanotube and other Super-strong and lightweight materials with a wide range of properties, might lead to development of multifunctional materials. Moreover, in the future the self-assembling materials and fabrication system may even go further towards efficient, low cost and time-consuming constructions (John et al, 2005; Niroumand et al., 2013b). According to another hypothesis, in a promising future the structural material could support dynamic in addition to static. For instance, the structural parts could be remodeled in order to dynamically respond to load like the structure of human bone (Oxman, 2010). All these advances could be predictable, as the revolutionary progress in the field of structural materials during the history was successfully developed. Likewise, in the future in addition to technical, functional and mechanical performances, intelligence and sustainable consideration of structural materials will be important.

From material fabrication and construction points of view, the age of mechanical linear production and division of labor is ending. In the future, the conventional manufacturing process may not exist, because new technologies always are offering innovative and lower-cost manufacturing methods as in the 20th century the float glass manufacturing system replaced the old glass production methods. As we have previously discussed, by advances in digital design and manufacturing techniques, the possibilities of 3D printers and robotic arms for construction systems are developing. These technologies have not found their place for large-scale buildings, however, in future they could put us one-step closer to sustainable building construction. It has been predicted that in the future, robots and 3D printers might be available in the construction site for producing materials, and fabricating furniture and building components simultaneously. This progress could result in faster, energy and resource efficient, and cost effective construction with minimum waste. As a result, by integration of design, modeling, and fabrication into one process a more sustainable approach might be achieved (Mori, 2002).

It is envisioned that in the future, 4D printed objects with the ability to respond to their users' needs, grow over time, and adapt to their surrounding environment might be developed (Oxman, 2012). Hence, partitions, surfaces and furniture could gain ability to be physically transformed in a reversible way, and to be optically controlled in order to be adapted to the clients' taste or any style. These could be important due to users' needs for variable, flexible and changeable styles in their tiny living environment in the future. In general, material experimental, tactile, and spatial properties would be developed for further advances in flexible, adaptable, and intelligent design. On the other hand, an immaterial stimulus may exceed upon future spaces, which deals with the intangible and deeper dimensions of design and tries to move away from material ties. Mori (2002) has predicted that in future, the spatial configuration of the space may change by immaterial. The light, sound, smell, and fog can signify the boundaries and threshold of spaces instead of conventional solid walls. However, as discussed previously due to the human being's need and values, this revolution may just touch some particular public and exhibition spaces. Moreover, lightweight, easy to carry, and short-life structures may be developed as temporal shelter for the human body in response to human dynamic activities towards immaterial design.

## 4.2 Numerical Evaluation of Building Material Developments

In the following, the author proposed the hierarchy evaluation method in order to evaluate the role and influences of sustainability, technology, and designers and users' expectations as the main criteria for achieving the goal of material-aware building design. The hierarchical structure helps to acquire knowledge of a complex system and by defining its constituent parts helps to focus on one single component, and in parallel, on the whole system. In this system, each criterion can be defined by different intensities, which prioritized it through each period, and in respect to the others. The components for sustainability, technology, users and designers were shown in the previous chapters through their specific hierarchy. In the following figures, they are represented with a new graphic that defines their values from past to the present, as well as their future possibilities. In order to evaluate the numerical values of the main criteria from past to the future, each component is ranked either one or zero according to its possibility or ignorance in each period. Each period is demonstrated in the figure by a specific line type and numbers in the legend table are cumulative sum of the evaluated values up to the corresponding period (Fig 4.1, 4.2, 4.3, 4.4). The researched area is divided as Prehistoric times, Ancient times, Western Civilization, 1800-1900, 1900-1950, 1950- End of 20th century, End of 20$^{th}$ century-2000, 2000-present, and Near future, which includes the sum of the all values for each criterion. For instance, the component value for the sustainability in ancient time (8) would be achieved through the sum of its relevant sub-criteria (5) with its previous period(s), which is the prehistoric times with value of 3 (Figure 4.1). Thereby, the component value for each period includes the value defined in the hierarchy legend for its previous period in addition to its specified components. This method has been used to calculate numerical value for the rest of criteria in each period.

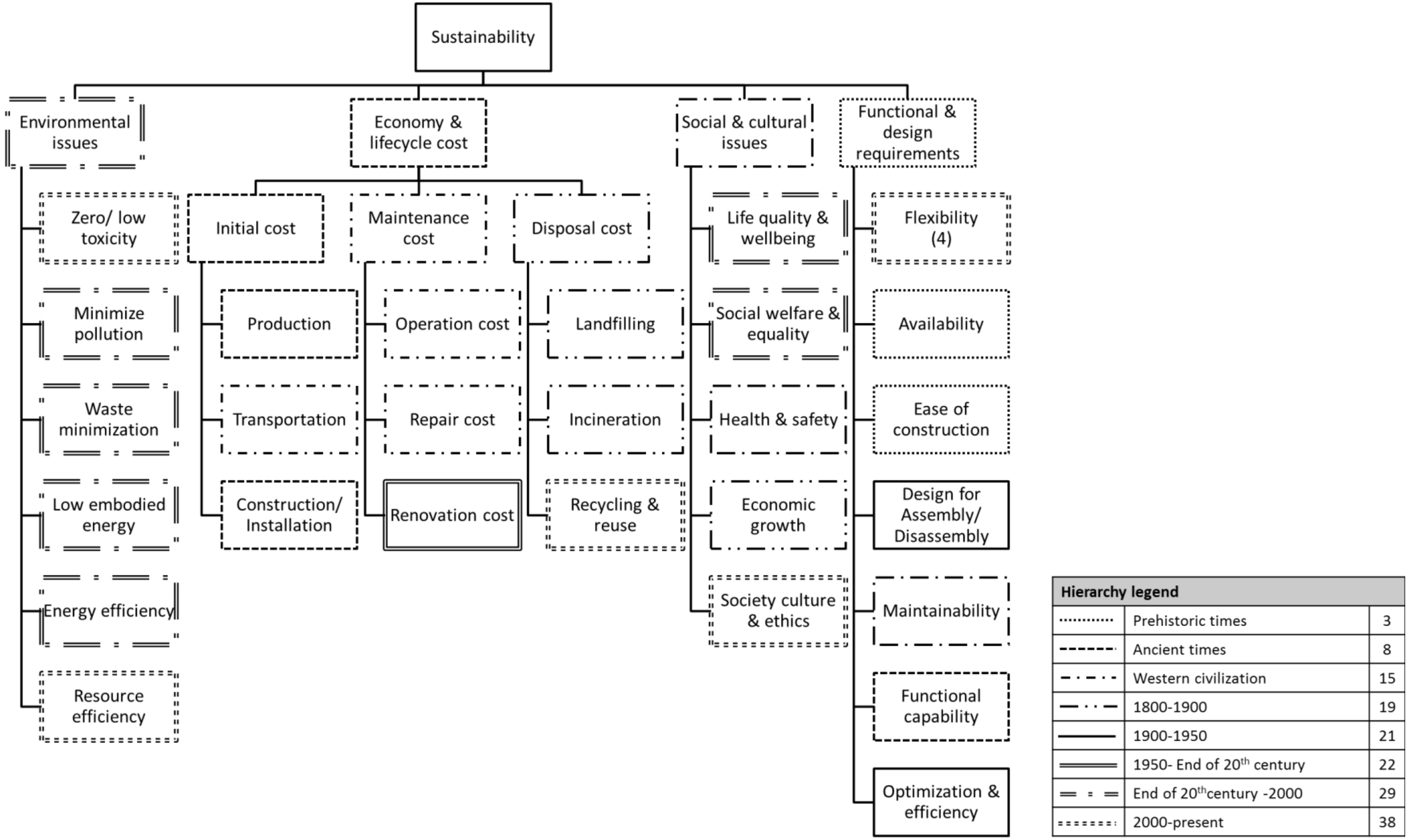



Figure 4.1: Hierarchy of initial criteria for evaluation of sustainability criteria from the past to the present

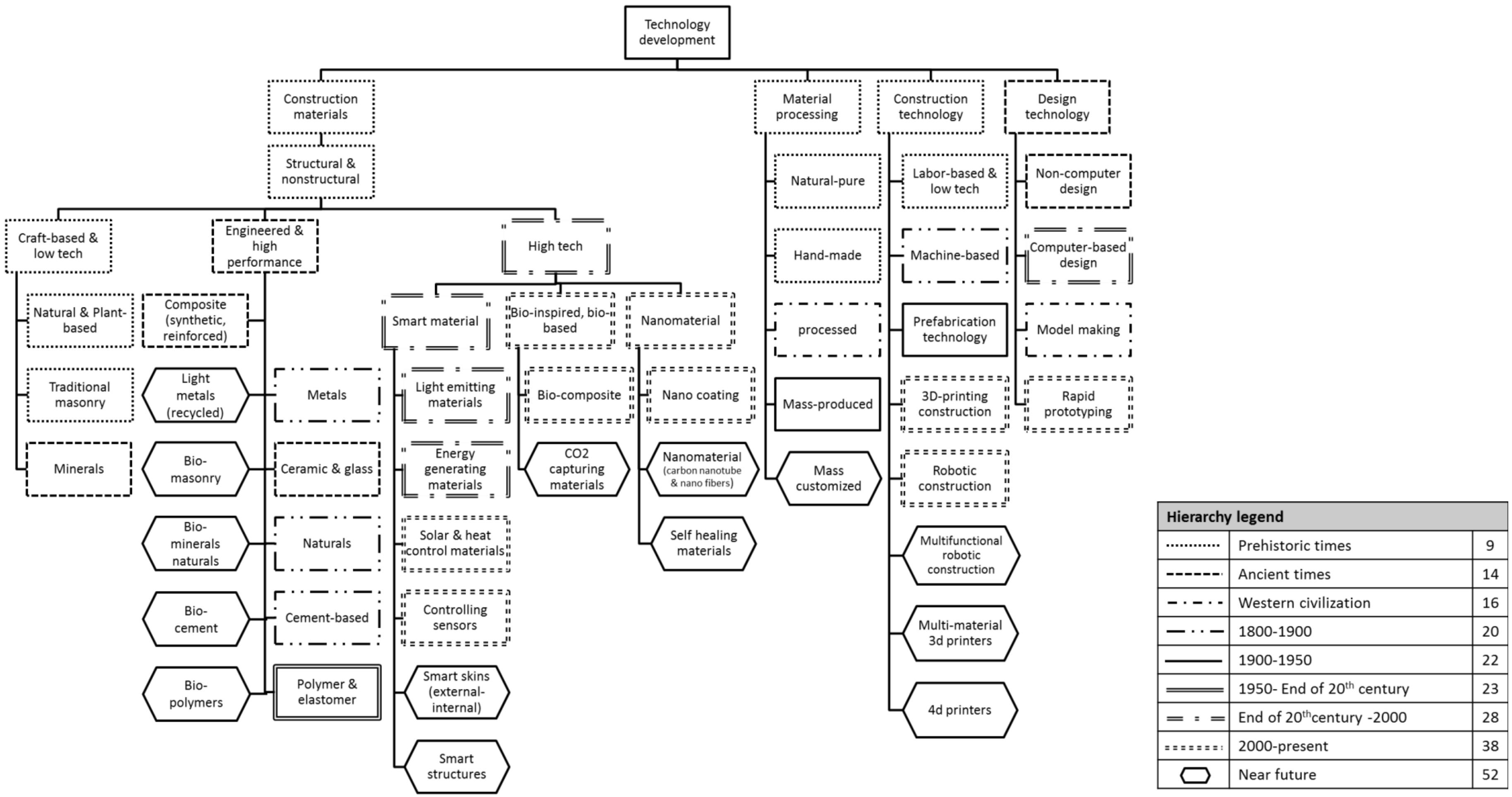



Figure 4.2: Hierarchy of initial criteria for evaluation of technology developments from the past to the near future

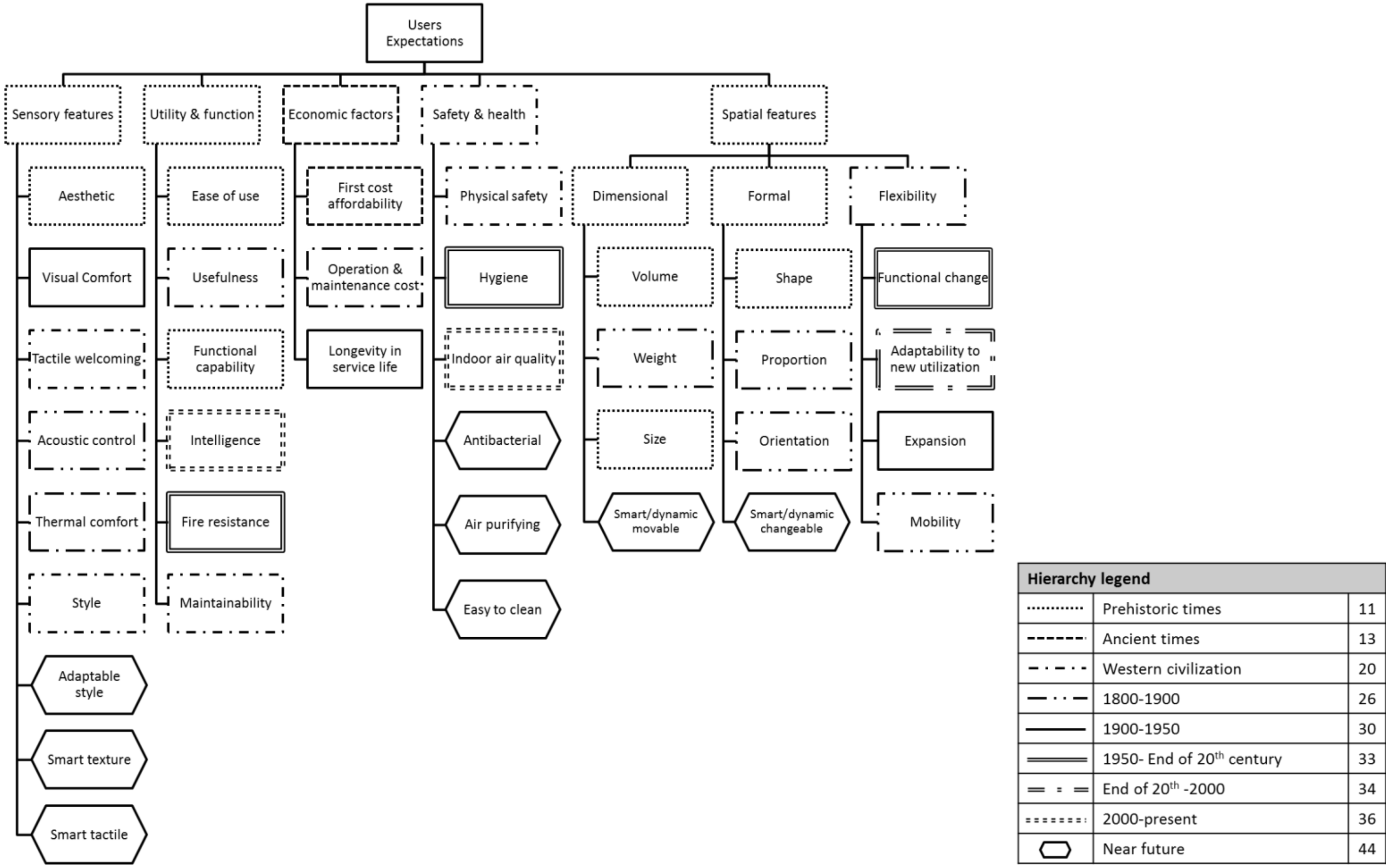



Figure 4.3: Hierarchy of initial criteria for evaluation of users' expectations from the past to the near future

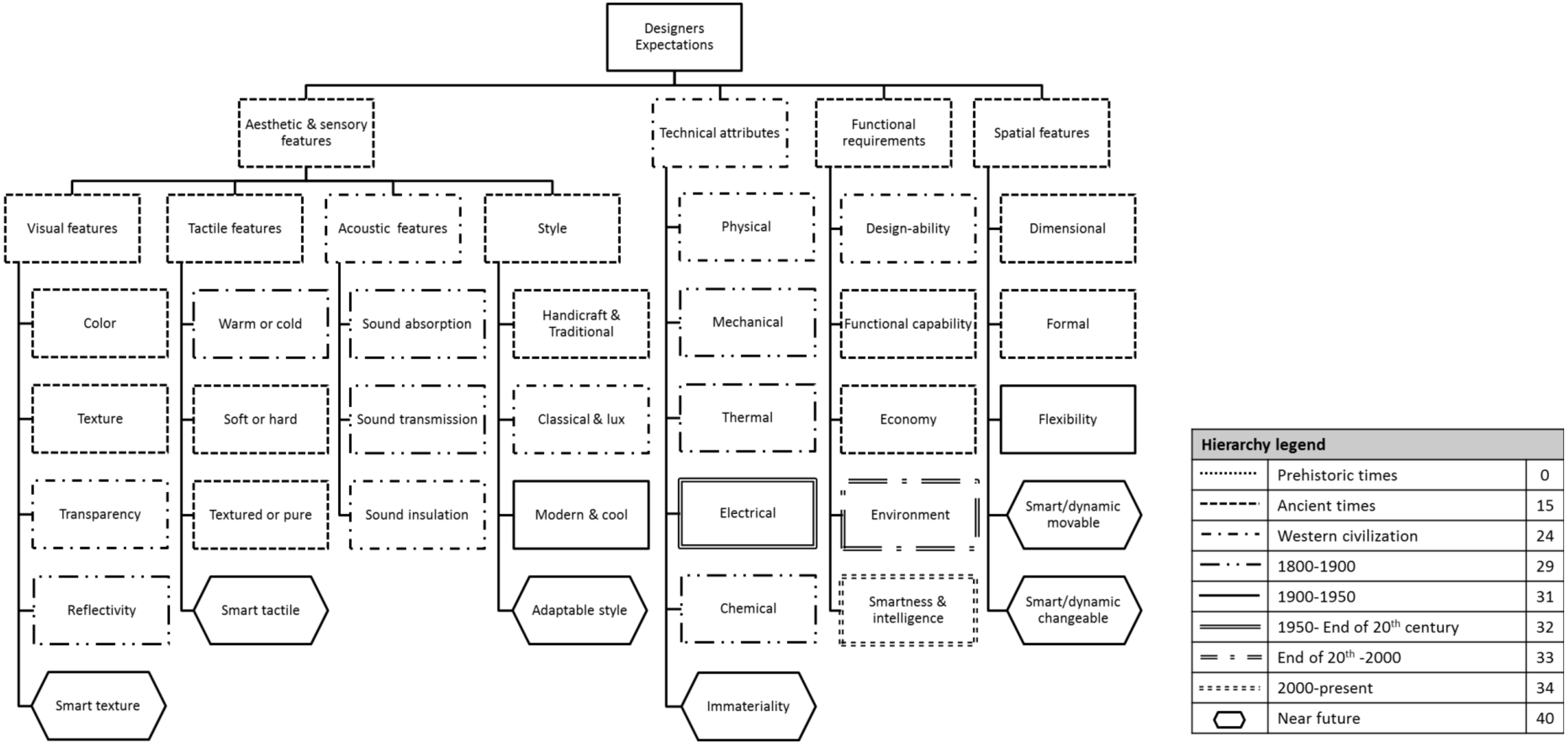



Figure 4.4: Hierarchy of initial criteria for evaluation of designers' expectations from the past to the near future

Because the progress of technology and other criteria are in accordance with the aims towards the benefits of sustainability, the value of sustainability in the future is achieved through the sum of the other possibilities for the future of building material developments (Fig 4.5). Therefore, according to the figure 4.5 the future possibility of the building material development for the sustainability would be 23. In due course by referring to the numbers in the legend table of hierarchies (Fig, 4.1, 4.2, 4.3, 4.4), the sums of all values for the main factors in each period are shown in the table 9.

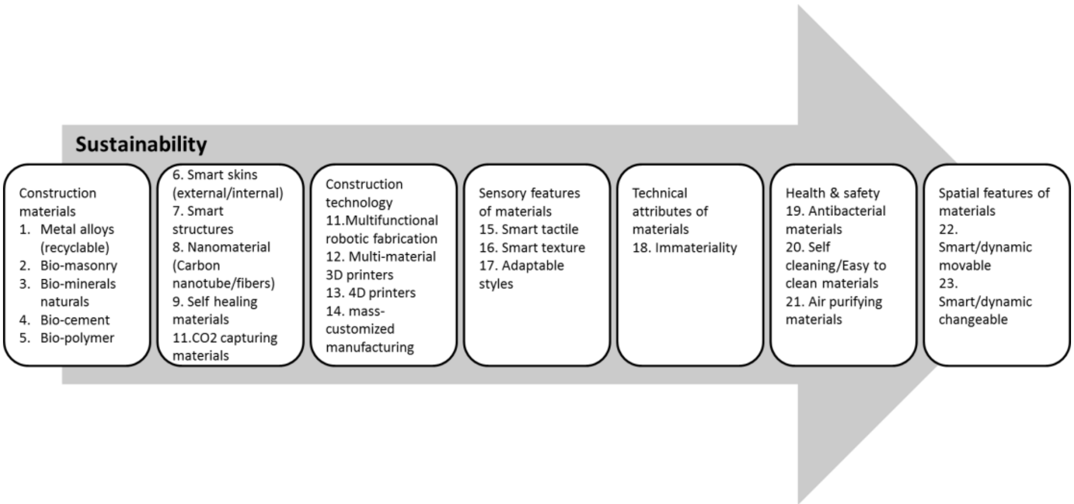



Figure 4.5: The future possibilities for the sustainability criteria

Table 9: The sums of all values for the main criteria in each period

| Material development variables | | Prehistoric times | Ancient time | Western civilization | 1800-1900 | 1900-1950 | 1950-End of 20th | End of 20th-2000 | 2000-present | Near future |
|---|---|---|---|---|---|---|---|---|---|---|
| Sustainability | Environment<br>Economy<br>Society<br>Functional Requirements | 3 | 8 | 15 | 19 | 21 | 22 | 29 | 38 | 61 |
| Technology | Construction Material<br>Material Processing<br>Construction Technology<br>Design Technology | 9 | 14 | 16 | 20 | 22 | 23 | 28 | 38 | 52 |
| User | Users' Expectations | 11 | 13 | 20 | 26 | 30 | 33 | 34 | 36 | 44 |
| Designer | Designers' Expectations | 0 | 15 | 24 | 29 | 31 | 32 | 33 | 34 | 40 |

Based on the table results, a line chart is designed that shows the influences of technology, sustainability, designers and users in the selection and development of building materials from the past to the future. In the light of the evaluation results, the square dots in the figure 4.6 display the influence of sustainability, technology, designers and users in the future. It appears from the chart that the majority of criteria increase gradually until the end, while the sustainability is the leading one (Fig 4.6).

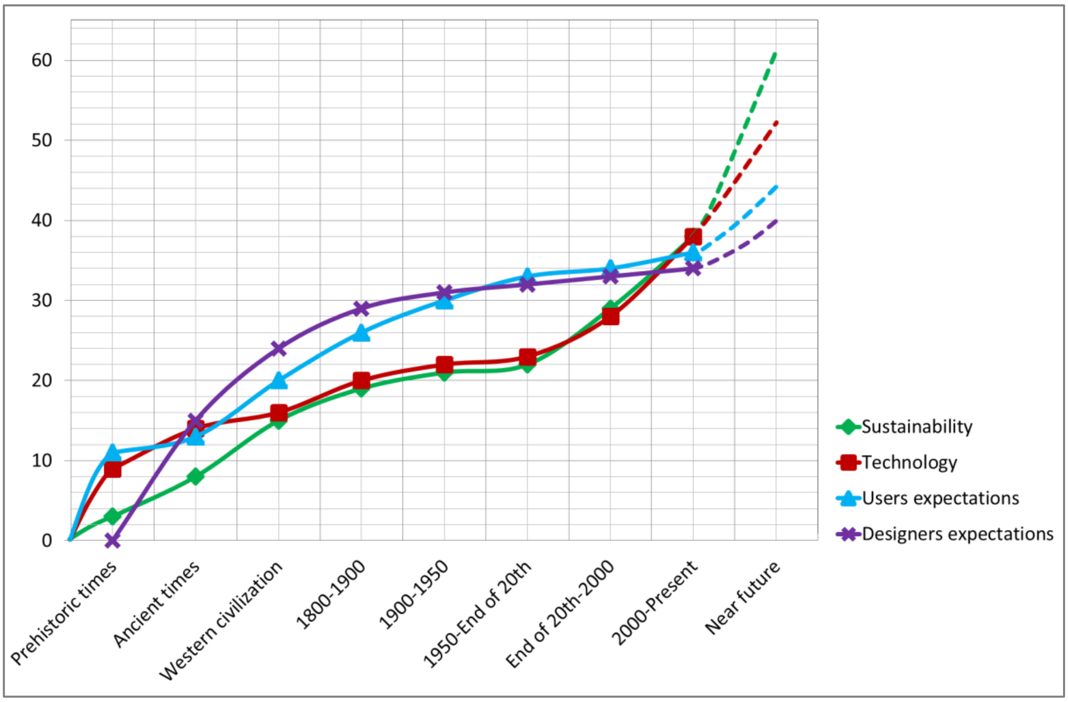
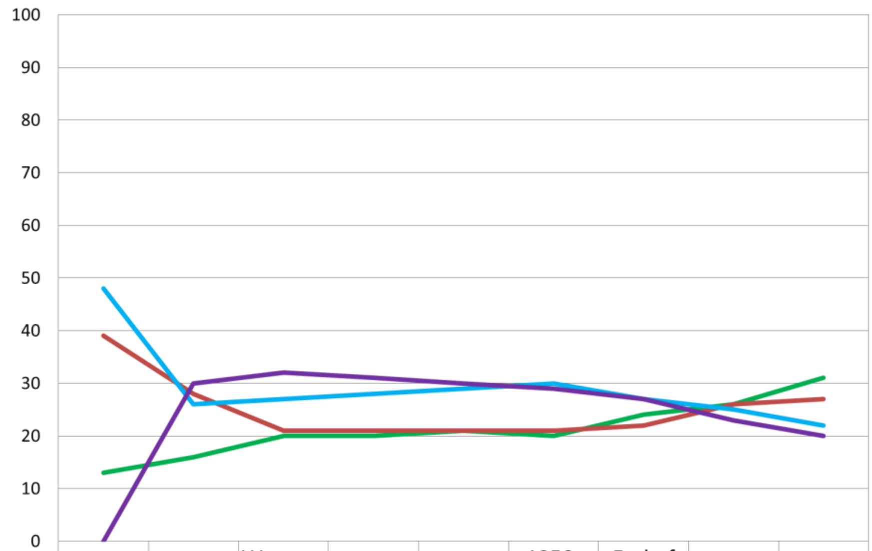



Figure 4.6: The influences of sustainability, technology, designers and users in the selection and development of building materials from the past to the future

Furthermore, the level of contribution of each criterion in response to the whole of the system for each period can be expressed as a percentage in another diagram (Fig 4.7). Although, the previous diagram shows that the influences of all factors increase along the time, this one compares the levels of contribution of sustainability, technology, users and designers for material development in each period. The result indicates that the relative percentage of sustainability at first was only 13%, while at the present time it increased to 26%. Therefore, increases in the share of sustainability in the recent years and in the future (31%) are considerable (Fig 4.7). At the end, it should be highlighted that the results do not imply that other factors have lost their importance, while help to compare the amount of contribution of each factor with each other and in response to the whole of the criteria. Thereby, another outcome of evaluation chart is to gain better understanding of the necessity for each criterion.




| | Prehistoric times | Ancient times | Western civilization | 1800-1900 | 1900-1950 | 1950-End of 20th | End of 20th-2000 | 2000-Present | Near future |
|---|---|---|---|---|---|---|---|---|---|
| Sustainability | 13 | 16 | 20 | 20 | 21 | 20 | 24 | 26 | 31 |
| Technology | 39 | 28 | 21 | 21 | 21 | 21 | 22 | 26 | 27 |
| Users expectations | 48 | 26 | 27 | 28 | 29 | 30 | 27 | 25 | 22 |
| Designers expectations | 0 | 30 | 32 | 31 | 30 | 29 | 27 | 23 | 20 |

Figure 4.7: The levels of contribution of the each criterion in response to the whole system

From the result of evaluation charts, in the future most importantly the sustainability issues with designers' contribution must direct technology to develop sustainable building materials. More specifically, by the help of biological material science and engineering, bio-base materials such as bio-composites, bio-polymers, bio-masonry, and other sustainable materials with high level of recycled content should be placed as the main priority in material scientist studies and designers practices. Likewise, the self-supporting, self-efficient and intelligent skins that respond intelligently to the environment and human needs should be expanded in the field of material technology. The new design and construction technologies such as 3D printers and robotic devices must be developed towards faster and sustainable construction of buildings. Thus, digital design and construction technology by changing the way that we build things might significantly contribute in the progress of design and construction by designers. In addition, studies on the application of nanotechnology in architecture must be encouraged for the benefits of the future generation of building materials. Furthermore, designers and material engineers should put effort into designing materials that support a wide range of functions in variable visual and dynamic spatial features with respect to customers' personal and social expectations. Finally, material scientists and designers should utilize the last technologies with the assistance of the science of material engineering and biology to provide the benefits of the environment and the future generations.

# Chapter 5

# CONCLUSION

This research, instead of focusing only on one problem aimed at solving multiple issues and collecting principles from different conceptual theories, it examined most influential factors in the development and selection of building materials from the past to the present. Furthermore, it defined material-aware building design as a comprehensive framework, and sustainability, technology development, users and designers' expectations, as the main drivers to achieve its goals. Then, the role and importance of each factor, in addition to the future needs, possibilities and challenges for the selection and development of materials were explicated. Finally, the future through the lens of building materials developments, according to all examined data during the research, was evaluated.

Over the long history of building materials, different influences accelerated or postponed building material developments and it is predictable that economic, environmental, cultural or technological changes may continue to affect this progress in the future. Most importantly, because of the environmental concerns, new changes have defined the direction of technology towards more eco-efficient building materials. On the other hand, new construction materials and manufacturing technologies from the industrial revolution highly changed the face of our buildings. Thus, it can be assumed that by solving the problem of high cost or lack of reliability of bio-based, engineered & high performance, smart, and nanomaterials, their structural and non-structural applications must be developed. Generally, due the importance of eco-efficiency, the focus should be on recyclable and bio-gradable materials with recycled content. In fabrication and construction technologies also, the revolution of 3D printers and robotic arms for construction of small-scale products to large-scale buildings may provide faster, lower cost and resource-efficient construction methods. Likewise, 4D printers, self-assembly structures, and immateriality are envisioned as other forward-looking concepts possible for the future. Moreover, the users' expectations and values are likely to influence all these developments. Accordingly, in the future, personal, social and cultural dimensions would define the spiritual and visual aesthetic. Besides, the science in support of innovative technology solutions would power the technical, functional and spatial aspects of the material developments.

From the results of evaluation section, in the future most importantly the sustainability issues encompassing the environmental concerns and the human rights may define the priority and limit in the selection and development of building materials. Consequently, the best results of material development in order to solve the paradox within the research problem would be achieved through a 'material-aware building design framework', and by creating a sequential relationship between technology, environment and human beings. At the present time the green and cradle-to-cradle certificated building materials, and in a promising future, innovative and bio-inspired materials would be suited to achieve better results. In general, adaptability, multi-functionality, effectiveness, productivity, creativity, quality, optimization, recyclability, diversification, localization and innovation are expected to create the future of building material developments.

To sum up, the proposed framework can be examined through its criteria and sub-criteria as a useful tool for designers and architects, who are willing to have a material-aware design approach and enhance the quality of their design towards environmental responsibility, human wellbeing, and adaptability to the future needs. In addition, it showed the target and priorities to material scientists and engineers by foreseeing the future of building material developments, and opened the way for future researchers. The further stage of this research would be analysis of material developments, possibilities and challenges for a specific group of structural and non-structural materials to propose the best alternatives for future developments.

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