Towards Novel and Appropriate Smart Buildings "Beijing Water Cube".

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Abstract: - Smart Architecture is considered as the most prominent aspects of new millennium. It depends on using modern techniques and information technology, working in an integrated manner so that the building performed its function in time. Water Cube has become an icon of a 'new Beijing' in the short time since its opening. This paper examines how Beijing tried to use smart components to fight its spatial and environmental problems, and create a new image for novel and appropriate smart building. So Beijing Water Cube has been identified in terms of general information about historical background, its construction, and its basic smart component (Smart materials - Smart skin - Smart structure - Smart Systems), reaching to learned lessons towards novel and appropriate smart buildings.

Key-Words: - Smart Architecture - Smart Building – Novel – Appropriate – Smart Materials – Smart Skin – Smart Structure - Smart Systems.

1 Framework

1.1 Introduction

The human aims through technology to control the environment and its changes, by creating a small environment responding to his needs and appropriate him. So, the recent period of the twentieth century has a great developments in the fields of technology and computer use. This made a significant impact on architecture, so smart architecture trend appears.

1.2 Research Problem

The main problem of the research is the absence of applying novel and appropriate features on smart buildings in Egypt, as smart buildings is evaluated only by the amount of recent technologies used in these buildings.

1.3 Research Objectives

The research's two main aims are as the following:

a. Finding the novel and appropriate features of smart buildings.
b. Finding a criteria to evaluate the novelty and appropriation of smart buildings.

1.4 Research Methodology

The research will follow inductive and analytical methods to achieve its goals, as the following:

a. Inductive Method

The research study definitions about smart architecture, its features and the components of smart building. The research also study definitions about novelty and appropriation, and identifying how to evaluate its presence in the building.

b. Analytical Method

The research analyzes an international case study according to the availability of smart architecture's components and evaluates it according to the research's evaluation checklist.

2 Smart Architecture

Smart building can decide on time, the most effective ways to create an environment and sustainable responsive [1], to raise the efficiency of its occupants with the lowest possible costs

throughout the life span of the building [2]. So it can be defined as [3]:
"The building which accommodates the latest technologies of the age, which make it capable to response the demands of the occupants and adapt internal and external conditions".

2.1 Smart architecture generation

There are three generation for Smart architecture which are as the following [4]:
a) Automated Buildings (1980 -1985).
Buildings that have a group of innovating technology controlled automatically in order to perform its work.
b) Responsive Buildings (1986- 1991).
Buildings that have the ability to respond the changeable needs.
c) Effective Buildings (1992 until now).
Buildings that represent responsive environment to achieve its work.

2.2 Features of smart architecture

There are three main features for smart architectures appears according to smart architecture generations [4], which are as shown in Table 1:

Table 1 Features of smart architecture [3].

Main features	Secondary Features	
Automation	Building management	
	Communications & office automation	
Responsiveness	Responding to users' needs	Limited response
		Smart response
	Responding to environmental changes	Limited response
		Smart response
Compatibility with the Environment & Sustainability	Environmental data collection	
	Efficiency of the internal environment	Lightning
		Ventilation
		Thermal
	Preservation of energy	

2.3 Components of smart architecture

The spread of the concept of smart buildings leads to the appearance of numerous derivative items, which later became the fundamental components of smart building and also affect the degree of intelligence of the buildings [4]. These components are as the following:

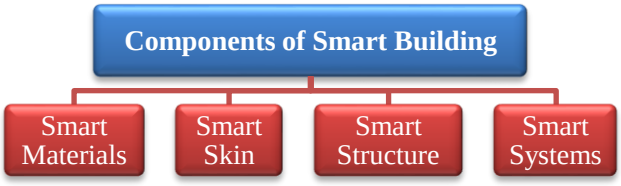

Fig. 1 shows the components of Smart Building.

a. Smart Materials is distributing some actuators and electronic models through the material, which leads to a major developments in the material properties. Giving it the ability to respond the changes around them and interact with them to be suitable for the functionality that is prepared for it [5], as in fig.2. It can be classified into the following:

- Using smart materials in the structure.
- Using smart materials in environmental treatments.
- Using smart materials in the outer skin.
- Using smart materials in interior finishing.

b. Smart Skin is integrating sensors and controllers with the outer skin of the building to control the climate change inside and outside the building, changing the ordinary skin to climate organizer skin[6], as in fig.3. It can be classified into the following:

- Using smart facades.
- Using smart roofs.
- Using interactive walls.
- Using smart shades.
- Using smart windows

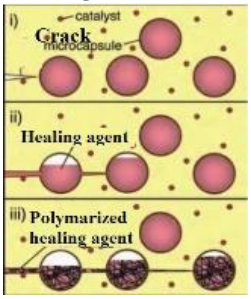

Fig. 2 Self-Healing material [7].
Source: (White, 2001)

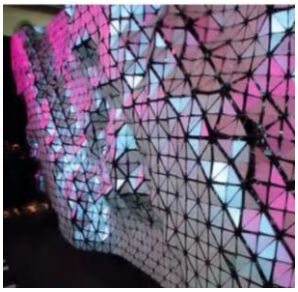

Fig. 3 Interactive interior wall [8].
Source: (Addington,2005)

c. Smart Structure is providing the structure systems with sensors and actuators which can decrease undesirable effects or increase the desirable ones [9], as in fig.4. It can be classified into the following:

- Structural Health and Safety Monitoring.
- Providing stability and balance using smart units.
- Analyzing and Designing using the computer.
- Using automated construction equipment.

d. Smart Systems is a set of inputs that are prepared and processed by a certain ways to get to a specific outputs to achieve a certain goals [10], as in fig.5. It can be classified into the following:

- Heating and cooling systems.
- Energy management systems.
- Safety and security systems.
- Fire protection systems.
- Communications systems.

- Management of natural resources Systems.
- Industrial lighting systems.
- Circulation systems.

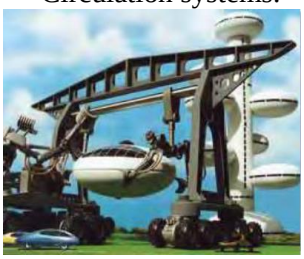

Fig. 4 Automated equipment [11]. Source: (Fresco, 2007)

Fig. 5 Identification Systems [12]. Source: (Kussul, 2010)

3 Novelty and Appropriation

The research will define novelty and appropriation, which are as the following:

3.1 Novelty

It means creative product is unprecedented innovated, unexpected and surprising [13].

3.2 Appropriate

It means valuable, aesthetic, adaptable, adjustment and achieving useful benefits either one or more benefits [13].Choosing an appropriate technology, was viewed as being the technologies contributing most to economic, social and environmental objectives.

4 Case Study: Beijing Water Cube

Case study is chosen according to the following criteria:

1- Building known for its intelligence, and made a leap in history of buildings.

2- Building covers the three eras of Smart Architecture generations.

3- Buildings have already been implemented.

So Beijing Water Cube is chosen, as it has already been described as creative, novel and wondrous. This smart building is designed to be able to create a responsive, comfortable environment [14].

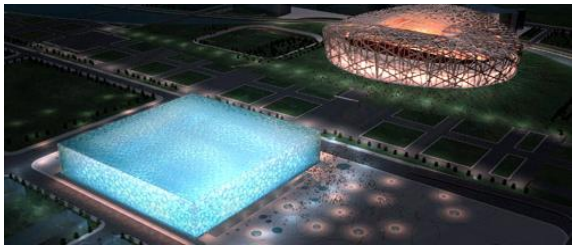

Fig. 6 shows external shot for Beijing water cube [15]. Source: http://www.ptw.com.au/ptw_project/watercube-national-swimming-centre.

4.1 General Information

- Project/facility type: Aquatic Centre.
- Location: Beijing, China.
- Commencement: 24 December 2003
- Completion: 28 January 2008,
- Owner: Beijing State-owned Assets Management Col, Ltd.
- Building Size: 177mx 177mx 29m high.
- Project cost: US$1 250 000 million.
- Architect: PTW Architects with China State Construction International Design Architectural Design and internal planning.
- Engineer: Arup with China State Construction International Design.

4.2 Historical Background

PTW Architecture Company and ARUP construction engineers in Australia teamed up with China Enterprise Confederation, led by a team of Chinese construction engineering company CSCEC, in order to get the largest importance world's contract, which is "Beijing National Aquatic Centre for the Olympic Games". The team Search for amazing design idea which is "soap bubbles" as in fig. 7. In July 2003 after four months of continuous work, the Water Cube design has been chosen among 10 international proposals by voting online [16]. After the completion of the Olympic Games, the center became a recreational facility open to the public. It was also used for sound and light shows during summer 2009 and also hosted a production of Swan Lake where it was converted to a ballet theater [17].

Fig. 7 shows soap bubbles design idea [18]. Source: https://www.youtube.com/watch?v=R66X3nroTC8

4.3 Description of the Building

Arup learned that the winning design would be nearby Olympic Stadium, the fantastic curvaceous red ‘bird’s nest’ structure. With this inspiration, they quickly decided that the swimming center should be a contrasting blue box [16]. Olympic requirements included a 50m competition pool, a 33m diving pool and a 50m warm up pool. The main pool hall was to have 17,000 seats for the games and then be reduced

to 7,000 seats with other facilities added in order to make the Centre a viable long-term legacy [17].

Fig. 8 shows inside Beijing water cube [16].
Source: (Conway, 2010)

4.4 Smart Components

Smart components which are used inside Beijing water cube are as the following:

4.4.1 Smart materials

a. Using ETFE in external skin

Ethylene tetra fluoro ethylene ETFE material, is a cousin of Teflon, which the team used to create translucent pillows for the building's cladding, is strong and resistant to degradation from ultraviolet light and air pollution. ETFE was more appropriate for such a use than glass, because of better acoustic and insulating properties, and it is lightweight, which eliminated the need for a secondary structure to support the skin [19].

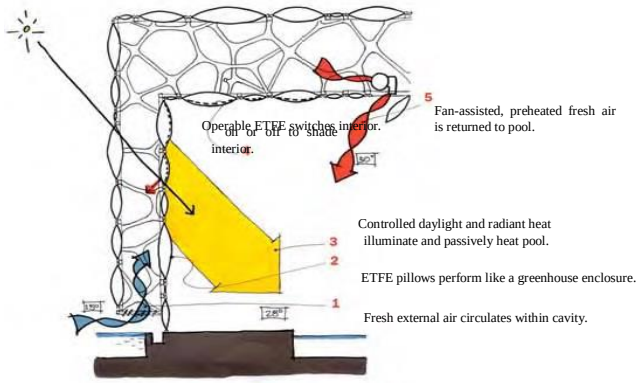

Fig. 9 Components of Smart skin of water cube [19].
Source: (Gonchar, 2008)

- Novelty: Using ETFE material in external skin is novel.
- Appropriation: Environmental, Functional and Formational benefits.

b. Using LATICRETE 9235 in interior finishes

LATICRETE 9235 Waterproofing Membrane, approved by the IBC (International Building Code), is a thin, liquid applied waterproofing and anti-fracture membrane that offers unmatched performance in pools, spas and continuous submersion applications, without any fear of breaking down or deteriorating.

LATICRETE has already received its Gold Medal, surpassing the competition with world-class tile and stone installation products, technical service, and the commitment of its China team in realizing the Water Cube [20].

Fig. 10 Interior finishes of Beijing water cube [20].
Source: (LATICRETE,2008)

- Novelty: Using LATICRETE material in interior finishes is novel.
- Appropriation: Functional and Structural benefits.

4.4.2. Smart skin

a. Using ETFE façade as a Smart façade

Arup's project management team had the challenge of coordinating 20 specialist Arup engineering disciplines, ensuring they were properly integrated, and that the complex façade of the Water Cube were properly understood and documented. External façade were classified as [19]:

- Physical: a physical interdependency exists, such as the location of an underground service or duct route.
- Functional: performance independency exists, such as power requirements or data connectivity.
- Organizational and contractual: a delineation in scope or contractual responsibility exists, such as the development of details by Arup's Chinese design partners CCDI based on Arup's scheme designs, or interfaces between civil engineering and architectural landscaping documentation.
- Operational: maintenance for equipment under warranty with the ongoing maintenance and replacement by the operator, and the short term responsibilities for Olympic overlay compared to pre-Olympics mode and then legacy mode.

- Novelty: Using ETFE façade as a Smart façade is novel.
- Appropriation: Environmental, Functional and Formational benefits.

b. Using movable ETFE units as a Smart Ceiling

Solar panels are used which preserve 20% of the solar energy that falls on construction. Sunlight energy is used to heat the air around the swimming pools and also heats the water. So it can also save up to 30% of the energy compared to other water park buildings [19].

It can control the stored self-generated energy between the two layers of ETFE by using several openings "vertical cylinders, clad top and bottom with circular panels". In winter, it keep these openings closed while in the summer these openings are opened by low and high levels to reveal heat energy [21].

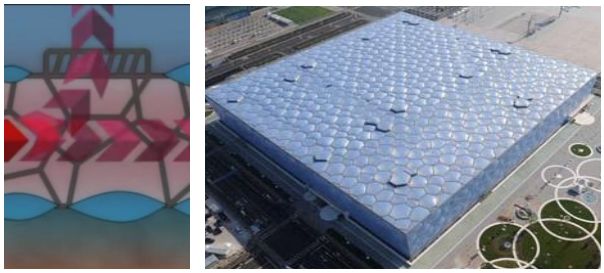

Fig. 11 smart ceiling in Beijing water cube [18].
Source:
https://www.youtube.com/watch?v=R66X3nroTC8.

- Novelty: Using movable ETFE units as a Smart Ceiling is novel.
- Appropriation: Environmental, Functional and Formational benefits.

4.3.3. Smart structure

a. Using sensors to keep Pressure inside each pillow to maintain the structural

The outside skin of the building consists of the ETFE pillows which made up of three layers (external, internal and Central). Pressure inside each pillow up to 200 Pa, so to keep the outside of the building, there are sensors to measure air inside the pillow to maintain the structural integrity of the building [18].

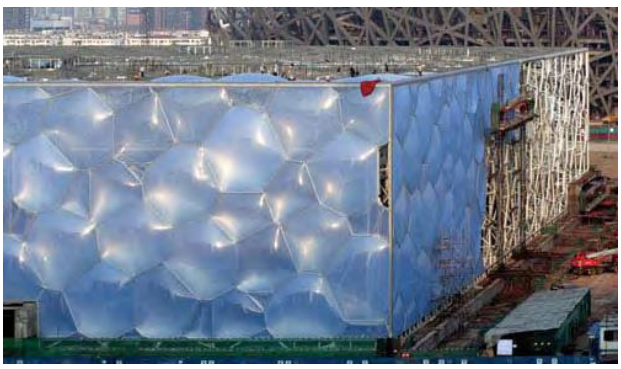

Fig. 12 keeping Pressure inside each pillow [19].
Source: (Gonchar, 2008)

- Novelty: Using sensors to keep Pressure inside each pillow to maintain the structural is novel.
- Appropriation: Economical and Technological benefits

b. Using ETFE as a self-healing material

ETFE material can withstand UV rays, high winds and snow, But it is very thin as it can be cut with a knife. Maintaining this building does not look like any other building maintenance, to repair any of pillows, it is Sufficient to paste the place of hole mode. The pillow has a self-healing property as it is under high pressure, will disappear by time [18].

Fig. 13 shows Maintaining ETFE material [18].
Source:
https://www.youtube.com/watch?v=R66X3nroTC8.

- Novelty: Using ETFE as a self-healing material is novel.
- Appropriation: Economical and Technological benefits.

c. Designing and analysis methods using Bentley

Arup developed a structure optimization program, which carried out the following phases [22]:

Structural Analysis Phase

Its job was to test for possible scenarios, challenging it to make the steel structure strong, but as light as possible.

Optimization Phase

During the optimization phase, 22 000 steel beam members under 190 different load cases were tested to determine the optimum size of each member that satisfied all design constraints, resulting in the minimum structural self-weight.

Design Phase

The benefit of an automated program is that allowing many design options to be repeated and considered quickly and accurately. 3D CAD modelling used by Arup was crucial in the creation of the 'Water Cube', modelling the complex structure quickly allowing for refinement and improvements in design.

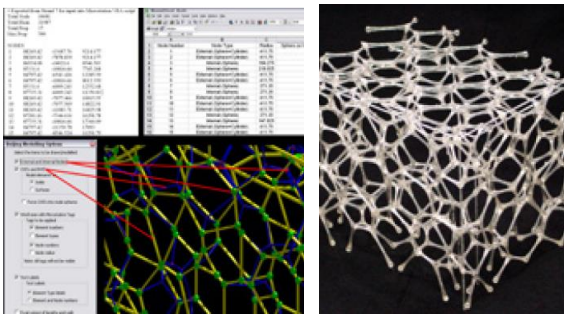

Fig. 11 prototype model with ETFE pillows [22].
Source: (AIA, 2004)

- Novelty: Designing and analysis methods using Bentley is novel.
- Appropriation: Economical and Technological benefits.

d. Using automated Air pump equipment

Beijing cubic needs to a huge consumer of energy air pump, for the 3500 inflatable pillow. To overcome this, the cube has been divided into 18 districts contain special fans which sends air into the pillows. Sensors are placed inside each pillows, so it will be informed if one of the pillows need to be further bloating or is it completely swollen, and these fans do not only minimal electrical power consumed. Air pump system that can maintain 100 000 m2 of ETFE swollen pillow by High pressure without wasting energy [22].

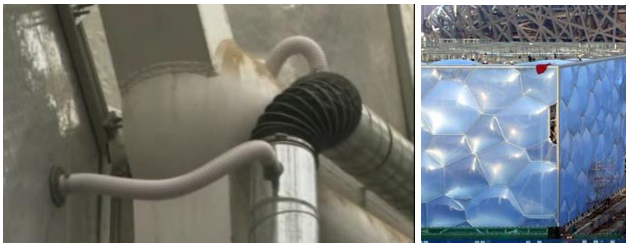

Fig. 14 shows Air pump system [18].
Source:
https://www.youtube.com/watch?v=R66X3nroTC8
Novelty: Using automated Air pump equipment is novel.

- Appropriation: Economical, Formational and Technological benefits.

4.3.4. Smart system

a. Using dark patterns as a heat transition organizing skin.

Variation in shading of the facade has ensured that fabric heat loads are minimized in summer but maximized in winter, when the solar sun is most beneficial. This is achieved by patterning the various layers of the facade with translucent painted 'frit' and by ventilating the heat out of the cavity in summer and containing it in winter. The positions and patterns of these translucent elements have been developed to respond to the daylight and the thermal requirements of the various building uses next to the facade [19].

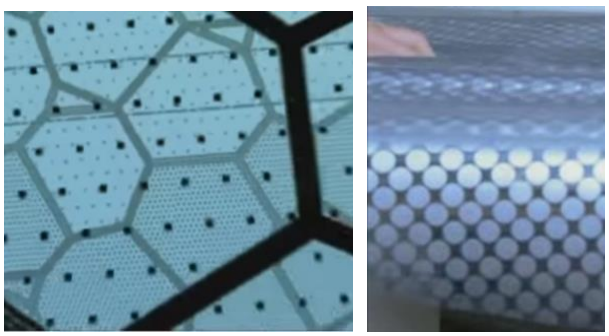

Fig. 15 shows patterns of translucent elements [18].
Source:
https://www.youtube.com/watch?v=R66X3nroTC8

- Novelty: Using dark patterns as a heat transition organizing skin is novel.
- Appropriation: Social and Technological benefits.

b. Using under-seat heating and cooling supply system

Air-conditioning will keep non-pool and office areas to around 23°C in summertime, with heat rejection of the air-conditioning warming the pools. The leisure pool must be kept at around 30°C while the competition pool requires 28°C. Spectators' areas, for example, are air-conditioned by an under-seat supply system, which will only be switched on during events. This targets the air-conditioning and prevents wastage to areas not used by spectators and competitors [14].

Fig. 16 Spectators area inside Beijing water cube [20].
Source: (LATICRETE, 2008)

- Novelty: This idea is not novel.
- Appropriation: Environmental and Technological benefits.

c. Using Access Card and electronic tickets as a security system

Controlling entrances and exits by using login Access Card for workers and electronic tickets for visitors. The building is monitored by Closed-circuit television (CCTV) systems [22].

Fig. 17 Main entrances of Beijing water cube.
Source:
http://www.fnrtop.com/vb/showthread.php?t=650916

- Novelty: This idea is not novel.
- Appropriation: Social and Technological benefits.

d. ETFE material as a Fire resistance system

With an estimated 20,000 people in the building at any one time during the games, the rigid Chinese code would have required 200m of exit doors – the equivalent of two sides of the building. This would not only spoil the look of the building but also create a security problem. ETFE material is used with detailed analysis of egress and circulation, so the number of exits was reduced, as ETFE material has the following characteristics [14]:

- It does not burn but it melts only during the presence of the flame as when the fire is kept away, the melting will stop.
- ETFE melting point is 270°, so fire will exhausted away and fumes will be absorbed by the building.
- The greatest attribute of ETFE in fire is that it shrinks away from the heat, thus effectively self-venting and letting smoke out of the building.

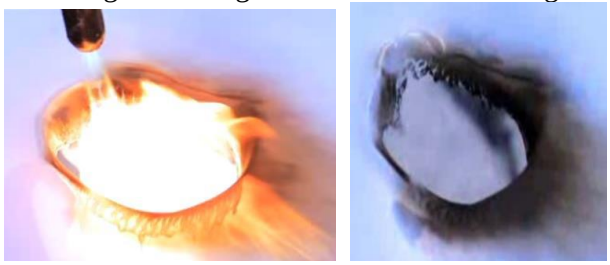

Fig. 18 shows Melting ETFE material.
Source:
https://www.youtube.com/watch?v=R66X3nroTC8

- Novelty: ETFE material as a Fire resistance system is novel.
- Appropriation: Social and Technological benefits.

e. Self-sufficient water system

The 100,000 square meters of ETFE foils (cushions) on the outer surface and roof façade can annually collect 10,000 tons of rain water. The Water Cube will recycle and reuse 80 percent of the water harvested from the catchments on the roof, pool backwash systems and overland flows, reducing its reliance on the district water supply system. “The idea was to make it as self-sufficient as possible” [19].

- Novelty: Using self-sufficient water system is novel.
- Appropriation: Economical and Technological benefits.

f. Using efficient communication systems

A range of project management tools established for Water Cube. These include simple protocols for shared servers and email filing between multiple offices, technical management of project interfaces, safety in design and construction sequencing, through to more complex programming applications that interface with Arup’s global cost monitoring system to provide detailed forecasting and performance reporting capabilities such as resource management and earned value management[14].

- Novelty: This idea isn’t novel.
- Appropriation: Social and Technological benefits.

g. Controlling lightning inside each pillow

The bubbles will steal the show, especially at night, when the Water Cube becomes a glowing coloured box with the help of LEDs integrated into the pillow frames [19]. The ability of the building to transform is perfectly in keeping with the design team’s goals: “Water cube has no fixed image,” says Wang. “It can reflect the sky, or it can have big waves”.

Fig. 19 lighting outer skin of Beijing water cube [18].
Source:
https://www.youtube.com/watch?v=R66X3nroTC8

- Novelty: Controlling lightning inside each pillow is novel.
- Appropriation: Functional and Formational benefits

5 Results Analysis

5.1 Novel and appropriate features of smart buildings.

There are seven novel and appropriate features of smart buildings as shown in Table 2:

Table 2 benefits from Beijing Water Cube

Functional Features (Benefits)

- Using interactive movable ceiling's units.
- Flexibility of adding smart systems in future.

Providing natural lighting by:

- Using smart material in the outer skin of the building which control el degree of passing natural sun light.
- Controlling the transparency of the outer skin.

Providing artificial lighting system by:

- Using motion detectors and monitoring devices to determine the level of lighting, movement and adjust the brightness.
- Controlling ceiling panels by computers.

Providing natural ventilation by:

- Using Double Skin Façade to allow air exchange by using automated fans.
- Using adaptable smart materials in outer envelope to prevent heat transfer.
- Using heating circles in the ground and ceiling

Providing artificial ventilation by:

- Controlling ventilation using smart systems
- Using smart sensors to collect data about internal and external environmental weather

Controlling security system by:

- Using surveillance systems for entrances and exits.
- Using digital units and access card to detect identity.

Controlling Firing by:

- Using Fire-resistant materials.
- Providing the building with (shelters - sprinklers - Smoke discoveries - audible warning signals).
- Using fire protection materials.
- Using automatic fans to expel the smoke.

Formational Features (Benefits)

- Using smart skin and controlling its lighting and colours by using computers.
- Providing buildings with automated external moving solar shades in its ceilings.
- Using double skin facades.
- Using large percentage of glass depending on the prevailing climate. So the percentage of the openings in the outer skin of the building increase. This will increase the transparency of the building allowing the integration between it and the environment.

Formal compatibility with external environmental factors like (Wind- Rain - Earthquakes) by:

- Using automated movable facades, automated movable roof, automated movable shades and automated movable windows which interact with the external environmental factors.

Structural Features (Benefits)

- Providing stability using smart elements like smart joints.
- Monitoring vibrations and earthquakes.
- The efficient use of new smart materials.
- Using smart materials in constructions which safe money on the long run.

Technological Features (Benefits)

- Using automated construction equipment which can save time and money.
- Using computer in analysing Structure systems.
- Developing new computer programs and Structural models design and analysis to present "Computer-Based Analytical Models".
- Structural Health Monitory using smart materials to monitor structural system and overcome the potential problems by using sensors in foundations and structural systems.
- Using automated maintenance tools for the outer skin.
- Using self-healing materials to allow easy maintenance.

Providing integrated communication systems by:

- The building equipped with High-speed wired and wireless connections.
- Using Electronic Mail, Teletext System, Telex & Teletext Systems, Videotext System, Telephone System, VPN service, local network Video System, video teleconferencing and Firewall.

Controlling the management of the building by:

- Controlling energy systems, natural resources systems, circulation systems
- Controlling Movement and communication elements by using smart elevators and lifts
- programming the computer for what is better as in (ventilation- lighting – fire resistance-control opening)

Environmental Features (Benefits)
• Providing natural lighting • Providing artificial lighting system • Providing natural ventilation • Providing artificial ventilation • Compatibility with external environmental factors like (Wind- Rain - Earthquakes)
Economic Features (Benefits)
• The efficient use new smart materials. • Using smart materials in constructions which safe money on the long run.
Social Features (Benefits)
• Controlling security system • Controlling Firing

From previous table, we can deduce the following:

a) Functional Benefit: It specializes in architectural design process and solving problems by creative ways.

b) Formational Benefit: Respecting the special composition forms during the process of innovative thinking.

c) Structural Benefit: Responsible for formation of internal innovated spaces and external masses using appropriate technology.

d) Technological Benefit: means innovation in the technical aspects of the architectural work.

e) Economic Benefit: means the ability to produce services on a continuing basis by creative ways, to maintain manageable levels of government and external debt, and to avoid extreme sectoral imbalances which damage production.

f) Environmental Benefit: means maintaining a stable resource base, avoiding over-exploitation of renewable resource systems or environmental sink functions.

g) Social Benefit: means achieving fairness in distribution and opportunity, adequate provision of social services.

5.2 Criteria of evaluation

The Criteria which can be used to evaluate the novelty and appropriation of smart buildings is as shown in Table 3.

Table 3 Evaluating novel and appropriate smart building.

Components of Smart Building		Novelty	Appropriate Benefits						
			Functional	Formational	Structural	Technological	Economical	Environmental	Social
Smart Materials	Using smart materials in the structure								
	Using smart materials in environmental treatments								
	Using smart materials in outer envelope								
	Using smart materials in interior finishes								
Smart Skin	Using smart facades								
	Using smart roofs								
	Using interactive walls								
	Using smart shades								
	Using smart windows								
Smart Structure	Structural Health and Safety Monitoring								
	Providing stability and balance using smart units								
	Analysing and Designing using the computer								
	Using automated construction equipment								
Smart Systems	Heating and cooling system								
	Energy management systems								
	Safety and security systems								
	Fire protection systems								
	Communications systems								
	Management of natural resources Systems								
	Industrial lighting systems								
	Circulation systems								

6 Conclusions and Recommendations

6.1 Conclusions

- Smart architecture can be used to overcome the challenges facing the construction of a novel and appropriate buildings.
- The right use of Smart Architecture preserve the environment and increase the level of novelty and appropriation of buildings.

6.2 Recommendations

These findings were translated into a group of recommendations addressed to a number of the concerned authorities, which are as the following:

- Introducing new courses in universities specially smart architecture technology and its role in achieving novel and appropriate buildings
- Increasing the awareness of architects about the right concept of smart architecture that have a positive impact on the novelty and appropriation.
- Doing integrated studies about environmental, social and economic aspects, of smart buildings that have a positive impact on novel and appropriate architecture.

References:

[1] Sherbini, K. & Krowczyk, R. "*Overview of Intelligent Architecture*" Saudi Arabia: 1st ASCAAD International Conference, e-Design in Architecture, 2004.

[2] Wingginton, M. & Harris, J. "*Intelligent Skins*" UK: Architectural Press, an Imprint of Elsevier, Butterworth- Heinemann, Oxford, 2002.

[3] Ibrahim, M. A., "*Intelligent Architecture - As an Approach for apply the Technological Development in the Environmental Control and Energy Efficiency in Buildings*" Egypt: unpublished Master Degree thesis, Faculty of engineering, Cairo University, 2010.

[4] Harrison, A. et al. "*Intelligent Buildings in South East Asia*" UK: Taylor & Francis, Milton Park, Oxford, 1998.

[5] Brownell, B. "*Transmaterial 2: a Catalog of Materials That Redefine Our Physical Environment*" New York: Architectural Press, 2008.

[6] Kronenburg, P. "*Flexible Architecture That Responds To Change*" London: Laurence King Publishing Ltd, 2007

[7] White S. R, et al. "*Autonomic healing of polymer composites*" USA: Macmillan Magazines Ltd, Nature, Vol. 409, February 15, 2001.

[8] Addington, M & Schodeck, D. "*Smart Materials and Technologies for the architecture and design professions*" UK: Architecture press an imprint of Elsevier Linacre House Jordon Hill, Oxford, 2005.

[9] Tzou, H. S. & Anderson, G. L. "*Intelligent Structure System*" USA: Kluwer Academic Publishers, Springer Science and Business Media Dordrecht, 1992.

[10] Spetzer, E & Katz, D. "Intelligent Buildings Systems Workshop Design concepts for an intelligent Building system" New York: Syracuse Center of Excellence Syracuse, 2006.

[11] Fresco, J. "*Designing the Future*" USA: The Venus Project, Valley Lane Venus, 2007.

[12] Kussul, E. & Baidyk,T. "*Neural Networks and Micromechanics*" Berlin: Springer Press, Heidelberg, 2010.

[13] Hassan, N. M. "*The Creativity in Architecture: Concept - pillars - the historical development*" Saudi Arabia: Scientific publishing and printing presses, King Saud University, 2008.

[14] Arup, PTW and CCDI, "*Box of Bubbles: Visualization of the Entrance to the Water Cube – The China National Aquatic Centre*", China, INGENIA issue 33, December 2007.

[15] PTW official site. Retrieved October 13, 2016, from the world wide web: http://www.ptw.com.au/ptw_project/watercube-national-swimming-centre

[16] Conway, K. R. "Observations on the Nature of Computational Geometry" USA: The University of Washington, 2010.

[17] Telecom, C. "*Case Study, Water Cube, Beijing 2008 Olympic Games*" China, 2009. Retrieved September 15, 2016, from the World Wide Web: http://www.comba-telecom.com.

[18] National geographic, "*Beijing Water Cube*", 2015. Retrieved September 15, 2016, from the world wide web: https://www.youtube.com/watch?v=R66X3nroTC8

[19] Gonchar, J. "*Inside Beijing's Big Box of Blue Bubbles*" USA: issue of Architectural Record, Manhattan,2008.

[20] LATICRETE International official-brochure, "The Beijing National Aquatics Centre Project", July A-1902-1108, 2008

[21] Chen Y., "*Creating A New Image Beijing: Beyond The Olympic City*", Real Estate Research Quarterly, December 2012.

[22] A.I.A. "*Beijing National Swimming Centre China*" USA: American Institute of Architects, Building Information Model (BIM) Awards Competition, 2004.