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Smart Materials and Technology in Sustainable Built Environment

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Abstract

Growing interest in the study of smart materials and their applications in many industries, particularly in the domains of construction and building technology, has been seen throughout the past several decades. Despite the fact that smart materials are not very novel, researchers are working to build smart materials and construct a system that regulates and guides the materials to provide a living environment with more resilience and fewer adverse effects. In order to better understand the effects that smart material systems have on the design and construction processes, as well as to explore how to design building with better responsive characteristics, the research aims to investigate the qualities and benefits of smart material systems in the field of building design. Once this state of responsiveness is attained, it will provide users with the ideal environment as evidenced by the structural, climatic, and architectural outcomes. The use of smart materials has the potential to significantly improve the sustainability of buildings by emphasizing phenomena rather than material creations.

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Keywords: Sustainable Architecture, Smart Materials, Smart Structural Systems, Smart Technology

1. Introduction

Technology and uses of smart materials were always the part of architecture. Vitruvius said that "Architecture is a science arising out of many sciences and adorned with much and varied learning". From Egypt, Greece, Romans, Renaissance Architecture, everyone work on new technologies of that era. With the rise of the 19th century, we find the industrial era, in which construction was introduced by cast iron and later on rolled steel. In present we have Structural System. Architecture is always, coordination of technological experts for the perfect outcome. Architecture can be considered as the set of the four main components - Form, Function, Culture and Technology. Form, which is refers to the shape of the built mass in projects and the geometry of the built mass.Function, which is refers the how that space is working of functioning. Also, it includes the land uses that's mean the land uses in projects are for recreational purposes or for the industrial purposes. Culture, which refers to the architect's perception for the entire project or for a specified part. How architect's uses the local or a specified culture for the project. Using history, beliefs and philosophical foundations of society in projects. Culture is non-physical context. Last one is Technology, which refers to the construction process in architecture for a project or work. Technology is about the techniques, what types of materials used for construction and the construction systems.

Material is a part of the construction process. So, some special kind of materials are used in the construction process which are later useful for the building sustainability, also for the users or occupant of that building and spaces. These materials can be natural or can be created by the mankind for the future purposes and benefits. Some kind of extra properties are given to these materials or they already have it. These materials are called now smart materials in architecture. Smart Materials and Sustainable Technology helps to improve the quality of life of the habitat and saves resources like time, money, materials etc(Anand et al., 2023).

Moreover, smart materials and sustainable technology can help to achieve sustainability in architecture which will be economically viable, socially acceptable and environmentally friendly. These two increases efficiency & simplify construction work and also provides flexibility in designing & planning of projects(Li et al., 2017). Its need of the time because we have limited resources and there is a huge gap between demand and supply.

The first objective of this article is to know the concept of Smart & Sustainability for Architecture in today's context, second is to find out available Smart Materials & Sustainable techniques which is used in Architectural Projects to construct Smart Habitat, third is to understand the positive & negative implications of Smart Materials and Technology with the help of case studies and last one is to give recommendation of smart materials & sustainable technology to improve quality of life in making of smart & livable Habitat.

This study is divided into four parts –In first part Literature Study done to know the recent & future materials and technology used in Contemporary Architecture through secondary sources, second part related to the literature case studies so that to collect information and data about

appreciation of stakeholders or users of smart materials and sustainable technology used in various projects. In third part Comparative Analysis of the Case studies is done to find the positive and negative aspects on the basis of various indicators/variables. Last part is related to discussion on consideration of positive aspects and possible approaches to solve the negative aspects.

2. Literature Study

We are all conscious of what smart buildings are and the way they need to start adding to the lives of one and all. To mention this smart revolution has been adopted too fast and unnecessarily, it has provided some very tangible benefits to its users. In the case of any type of construction, the materials that are in use are quite plentiful, especially once we mention the development of smart buildings, these materials will not be heard before, but the relevance is that the regular element stands out compared to them. The rapid increase in climate change phenomenon led environmental degradation and also put stress on its resources. As urbanization has emerged as the symbol of development and building constructions form a part of that environment, therefore cause a larger part of environmental pollution. To overcome these issues innovative smart material has been used to enhance environmental sustainability, the cost effectiveness and security. New technologies and innovative materials are developed to fulfill these. They also provide creative solutions to long lasting problems like downgrading impact on environmen.Smart materials in architecture are materials that help users for their easy functioning in buildings and make them more efficient and durable. Today smart content is replacing installations in architecture. These materials help us adapt to environmental changes through their actions.

2.1. Definition of Smart Materials

Smart materials are created materials with the ability to respond in a special, advantageous way to changes in their immediate surroundings. Smart materials, as described by NASA, are "materials that (remember) configurations and can conform to them when given a specific stimulus". Smart materials and structures are described as those items that perceive environmental events, process sensory information, and then act on the environment in the Encyclopedia of Chemical Technology. In the third definition, acts are referred to as materials(Mohamed, 2017).

Smart materials, as defined in architecture, are high-tech materials that, when used in a structure, respond logically to climatic variations throughout the year. To provide comfort or meet human requirements, the atmosphere might be either hot or cold. Materials and systems that may responsively adapt to changing interior environments through material characteristics or material synthesis are referred to as "smart materials".

A logical continuation of the trajectory in materials research towards more selective and specialized performance is frequently how smart materials are viewed. According to this perspective, they resemble living things since they can conduct detecting and actuating activities as well as adapt to changes in their environment(Nilimaa, 2023). Alternatively, smart materials can modify themselves in response to an external stimulus by generating a signal of some kind.

2.2. Need of Smart Materials in Built Form

Smart materials can play critical role in building construction & development technology. These materials possess the ability to understand environmental phenomenon and react to them accordingly. They can change their color, shape, form and internal energy (Shape memory alloys- SMA possess ability to regain previously defined shape when subjected to thermal changes). These intelligent materials are used along with smart structure techniques to monitor the safety and serviceability of large engineering structure as well as their structural health.

2.3. Characteristics of Smart Materials

There are five fundamental characteristics which distinguishing a smart material from the more traditional materials that are used in architecture(Abdullah & Al-Alwan, 2019)–

1. Immediacy: they respond in real time;
2. Transiency: they respond to more than one environmental state;
3. self -actuation: intelligence is internal to rather than external to the "material";
4. Selectivity: their response is discrete and predictable;
5. Directness: the response is local to activating event.

All smart materials can be grouped into three type's characteristics(Bahl et al., 2020) -

I. Property Changing Materials;
II. Energy Exchanging Material;
III. Material Exchanging (Discrete size/location –Reversibility)

2.4. Classification of Smart Materials

Smart materials and its systems could be divided into two types (As shown in Fig.01) –

Type-I: Materials adapt to changes in stimuli from outside the environment by changing one or more of their characteristics (chemical, electrical, magnetic, mechanical, or thermal). By changing the material's microstructure, the energy input to a material alters its internal energy and changes the material's properties, such as the following(Abdullah & Al-Alwan, 2019):

- Thermochromics - an input of thermal energy changes the material's color.
- Phototropic - materials that change color when exposed to light.
- Magnetorheological and electrorheological - the application of a magnetic field (or for electro-rheological -an electrical field) causes a change in micro-structural orientation, resulting in a change in viscosity of the fluid.
- Thermotropic - an input of thermal energy (or radiation for a phototropic, electricity for electrotropic and soon) to the material alters its microstructure through a phase change. In a different phase, most materials demonstrate different properties, including conductivity, transmissivity, volumetric expansion, and solubility.
- Shape memory - an input of thermal energy (which can also be produced through resistance to an electrical current) alters the microstructure through a crystalline phase change. This change enables multiple shapes in relationship to the environmental stimulus.
- Mechanochromics - materials that change colour due to imposed stresses and/or deformations.

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- Chemochromics - materials that change colour when exposed to specific chemical environments.
- Electrochromics - materials that change colour when a voltage is applied. Related technologies include liquid crystals and suspended particle devices that change colour or transparencies when electrically activated.
- Phase-changing materials - use chemical bonds to store and release heat.
- Adhesion-changing materials - change the attraction forces of adsorption or absorption of atoms or molecules when exposed to light or electrical field.

Type –II: Energy is transformed from one form to another by smart materials. The energy supplied to a material alters the energy state of the material composition but does not affect the material itself; instead, it just causes the energy to change. Examples of this include(Bahl et al., 2020):

- Light-emitting materials, that convert an input energy to an output of radiation energy in the visible spectrum, are including,: Photoluminescents (input is radiation energy from the ultraviolet spectrum ;Electroluminescent (input is electrical energy) ; Chemoluminescent (input is chemical reaction)
- Piezoelectrics (an input of elastic energy - strain produces an electrical current. Most piezoelectrics are bi-directional in that the inputs can be switched and an applied electrical current will produce a deformation - strain).
- Thermoelectrics (an input of electrical current creates a temperature differential on opposite sides of the material).
- Photovoltaics (an input of radiation energy from the visible spectrum produces an electrical current.
- Electrostrictives (the application of a current produces elastic energy - strain which deforms the shape of the material).
- Magnetostrictives (the application of a magnetic field produces elastic energy - strain which deforms the shape of the material).
- Light Emitting Diodes - LEDs.

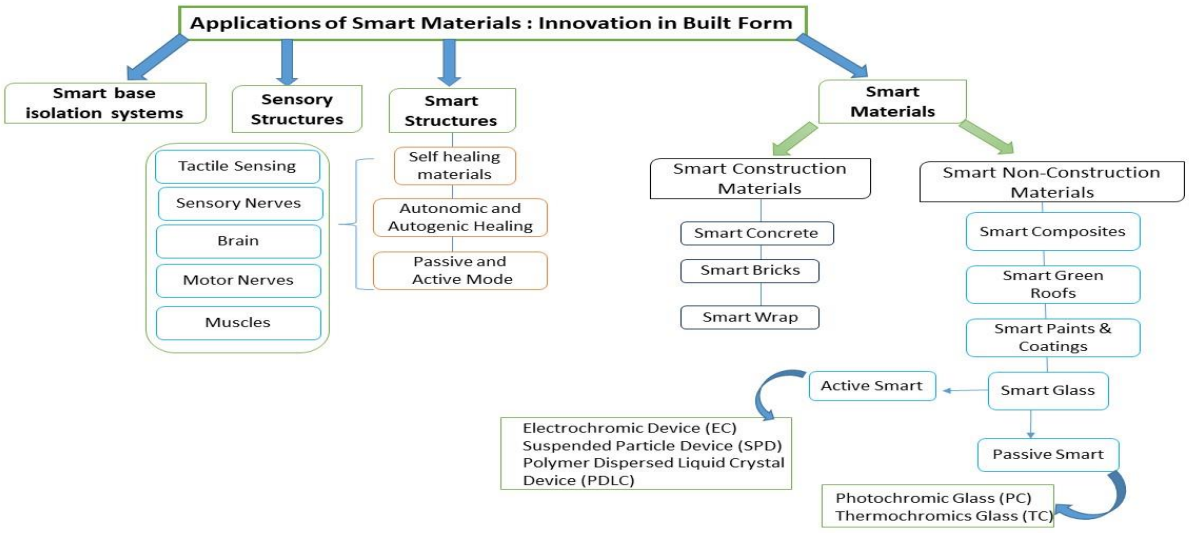

Fig. -01 Application of Smart materials in Innovative Architectural Built Form (Source: Author)

2.5. Application of Smart Materials in Built Form

Developments in the field of smart materials and the introduction of smart material systems paved their way into the wide range of application in architecture and major civil engineering constructions like buildings, smart bridges. They also proved to be beneficial in making smart concrete which ultimately provide higher potential and enhanced strength. Smart material systems in architectural practice provide flexibility in designing and planning of projects. "According to Ritter and Muller, a Smart material system in architectural practice are categorized by behavioral aspects into"(Malekizadeh et al., 2014):

- Structural Performance:
  1. Safety monitoring.
  2. Self-healing properties.
- Climate and Energy Performance:
  1. Latent Heat Storage.
  2. Adaptive Daylight Systems.
  3. Energy Harvesting.
- Architectural performance:
  1. Lighting and Displaying Technology.
  2. Space Division.
  3. Aesthetic and Entertainment Adaptations
  4. Self-Cleaning Technology.

2.6. Existing Common Smart Materials & Sustainable Technology

Use of Concrete : Come to think of it, tons of today's architectural thought process can be a reflection of what happened earlier. Builders are taking tons of ideas from development that took place an extended time ago. Adoption of these practices has become quite prevalent in today's smart structures. The critical deal will begin when concrete can continuously monitor, regulate, adapt and repair itself without the aid of any human effort. Materials such as nanometers, biomimetic materials, are ready to solidify within other skin-like forms (Bhaumik et al., 2023).

Use of Nano Technology : In space research, pharmaceuticals and industry, the newest materials are Nanotechnology-based materials. Considering the future Building industry Start adopting it. The way our resources are depleted today is about the conversion of existing building stock from an energy waster to an energy producer. However, this requires new technologies associated with renewable energy sources, which are quite important for specific manufacturing as this is also the field. Energy standards for buildings have become very stringent recently(Nilimaa, 2023). The use of traditional insulation materials often means an increase in layers of insulation in walls, floors and roofs. In cases after the adoption of smart technology in buildings, these above issues are well taken care of. The implementation of nanoscience can lead to significant improvements in the form of integration of renewable energy even within the energy efficiency levels of the building envelope. It balances aesthetic requirements with architectural constraints, considering every aspect without hindering the performance of a nanoscience building. Advanced insulating materials such as fiber-reinforced large blankets, vacuum insulated panels that are much thinner than previously used technology. These are designed to allow mixing of insulating material architecture, minimal burden, lack of thermal bridge and piping application.

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To maximize luminously transparency through technology, Self-cleaning and anti-reflective glaze are offered today. There is no doubt that today smart building materials are replacing building industry materials. Listed is the most important innovative building material that is making structures smart.

Transparent Wood : In past years, Development rise was very aggressive and intensive in concrete and other construction materials. One of the most important staple materials, which has made a mark for itself, is transparent wood. This material has better insulating properties than glass and is additionally stronger. It also makes it better biodegraded than plastic, making it among the few within smart building development.

Shapeshifting Metals : Then there are the shaping metals that change their shape, browsing the pressure when returning to their original shape after a short period of time. These materials are particularly useful within the development of buildings that lie within earthquake and hurricane-prone areas.

Use of Straw: It is a sustainable, inexpensive and ecologically friendly material that has proven its relevance to smart building architecture. Straw walls provide twice as much insulation than current regulations established by some countries. It should be noted that these straws have the ability to refund the fuel bill by up to 90%. This technology offers rock bottom carbon footprint and therefore the best operational CO2 performance of the system of construction available today. Straws also are low cost. Due to low cost, straws are widely available as food co-products. So, it will be very important for a low-carbon future. The importance of the above two can't be overlooked as they're not only pro-nature but are one among the simplest available and affordable materials that help us etch the dream of higher and smarter construction(Givoni, 1992).

Biodegradable Materials: To increase sustainability in construction we should first think about the construction methods which we are using nowadays, as traditional methods working is a collection of waste products and toxic chemicals after the completion. These remaining waste materials are non-bridgeable materials which takes hundreds year to degrade. So, using biodegradable materials in construction can lead us to a sustainable construction. Biodegradable materials are not harming our environment and they also not release such type of toxic materials(Gupta, 2017). We can use organic paints for walls. Also, biodegradable materials in foundation which directly connect to the ground.

3. Sustainable Technology

Sustainable is a composition of Sustain + Able. Sustain means “To keep up”, “to bear”, “to hold up” and “give support to” So sustainable means when someone complete our own needs or keep up to date (Youmatter, n.d.). So, by adding technologies and development to the sustainable means not only humans or user is satisfied with the needs or to up to date but also the social and the life on the earth i.e., environment. Main three pillars are the Environment, Social and Economic. If a process fits in these three categories then it called sustainable, otherwise not. For example, a process in which it is not socially accepted then it is not sustainable it’s viable. Same

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as when it is not environment friendly then its Equitable and when it is not economic then it's bearable but not sustainable(Lai et al., 2023).

Today buildings are becoming more energy-efficient and Sustainable through green technology(Himanshu Poptani, 2018). Buildings showing a lower carbon footprint and a reduced impact on the environment through green technology implantation(Tamura & Yoshie, 2016). Taken future in mind we preferred sustainable and energy efficient operated green technologies in the design, construction materials and also in structure. Today in green construction top sustainable construction technologies are:

1. Solar Power
2. Green insulation
3. The use of smart appliances
4. Cool roofs
5. Sustainable resource sourcing
6. Low-energy house and Zero-energy building design
7. Electrochromic Smart Glass
8. Water efficiency technologies
9. Self-powered buildings
10. Sustainable indoor environment technologies
11. Rammed Earth Brick

Solar Power: In green construction solar power is divided into two categories first one in Active solar power and second one in passive solar power.In active solar power, Sun radiation are absorbed by the functional solar system which increase the supply of electricity and used for the heating.While Passive solar power is totally based on design. Houses and building are designed in way that windows and opening are placed on a proper placement so sun ray can properly enter in the building and warm the spaces. Through this process uses of warmer in the house in winter periods are reducing.

Green Insulation: Insulation also play an important role in the construction of building and homes. On completion of project finishes are used which are very costly as well as they are made up of non-renewable materials. Green insulation gives us a way through which we can use old and used materials for insulation like newspaper and denim.

The Use of Smart Appliances: Today, with time changes and uses of technologies increases. Home appliances are used in the building, like Smart grid dishwashers, refrigerators, washing machines and Air conditioners are more energy saving. So as Sustainable Construction technologies for the construction of building are used so they the Self- sufficient appliances and energy saving are also used(Lai et al., 2023).

Cool Roofs: As roofing play an important role in the heat gain from the sunlight. So Cool roofs are the roofs which are used to reflect the sunlight and heat. It is a made up with the sustainable green design technologies (Himanshu Poptani, 2018). By using these types of roofing, we can reduce the temperature of the building in simmer more than 50 degree Celsius.

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Sustainable resource sourcing: As 3R (Reduce, Reuse, Recycle) important in sustainability. So, in this method the resource sourcing is all materials are made up from the recycled products. So, these materials are help in the environmentally friendly ambience.

Low-energy house and Zero-energy building design : In construction, the build of steel and concrete uses the higher embodied energy. So, to reduce the consumption of embodied energy we can use wood in the building for construction.

Sustainable green construction increases the flow of the air and reduces air leakage. These green construction techniques are based on the insulation and high-performance windows.

Electrochromic Smart Glass: There are many ways to encourage the sustainable construction. Electrochromic smart glass is one of them. This glass is used to as blockage for the heat to enter in to the building in summers. This glass works on process of electric signals, as signals blocks the solar radiation through the windows when we charged these electric signals. So, this type of products is really helpful for the building control system. As, glass not allowing the solar radiation in to the building. Through this technology we can save lots of cost in the HVAC system, Mechanical ventilation and heat control systems of the homes and commercial buildings(Zhang et al., 2021).

Water efficiency technologies: Today water consumption is high as well as wastage also. By using such technologies which allow reusing of water and efficient water supply system. Use of dual plumbing, greywater reuse, installing rainwater harvesting system which stores rainwater for the further use and water conservation fixtures. These systems installing in the building overcome the water wastage by 15% to address the freshwater shortages(Desai et al., 2019).

Self-powered buildings : Zero energy construction can be achieved through the construction of self-powered building.In this type of building, they can manage the consumption of our energy needs through generating our own power(Gupta & Tiwari, 2016). Sometimes building able to surplus the extra energy back in to the PowerGrid. Wind energy and solar energy is used. Wind energy used in the skyscraper where wind turbined are installed on the rooftops. Solar energy systems are in the large area projects where roof area is maximum so solar plates easily installed on the rooftops(Wu et al., 2023).

Sustainable Indoor Environment Technologies: Keeping the mind on the sustainable technologies and construction of a building. The occupant's health and safety are also important. It can be done only before the fully completion of building construction(Gamero-Salinas et al., 2021). So, we have to consider the nonhazardous elements, moisture free/resistance materials, Non-toxic materials and low volatile emission products keeping the safety and health of the occupants(Afreen et al., 2018).

Rammed Earth Brick: One of the ancient construction technologies is Rammed earth brick. Rammed earth bricks increase the environmental sustainability so this technology is re-introduced in the construction(Srivastav & Jones, 2009). Old process takes lots of time for

the preparation of rammed earth bricks but with the help of technological advancements made its easier(Anand et al., 2023).

4. Challenges of smart materials

Although smart materials are stunning and efficient in addressing the environmental challenge, they are rarely used in the construction of buildings. There are two possible explanations for why it isn't more common: practical and theoretical.

Practical Challenges: There are three primary characteristics: high expense, lack of cognition, and fear of danger. Smart materials should be made available to individuals in order to get around these obstacles. In this approach, advertisements are quite important. Smart materials should be used in highly visible locations in the following phase. People would get familiar with them and support their use if done in this manner. Finally, widespread acceptance of the usage of smart materials results in great demand and large manufacturing, which lowers the cost.

Theoretical Challenges: A new technique is not extensively adopted because of insufficient understanding and raw material availability. When it comes to smart materials, these two traits are absent since it is assumed that each material has a distinct supply of different sorts. Therefore, another field should be investigated to see why it is not widespread.

As a consequence of this in both domains of development, acknowledgement is the first step. To analyze the issues and provide remedies for this issue, diligent and exact investigation is required.

5. Architectural Design Framework for the Utilization of Smart Materials

Beyond individualization and customization, architects must also fulfil the demands of ongoing innovation while creating environmentally responsible architecture and achieving socio-technical goals using clever, cutting-edge materials, structures, and systems. The Socio-technical Theory System, shown in Fig. 2, may be used to reflect the market's ongoing demand for innovation in light of its intense competition.

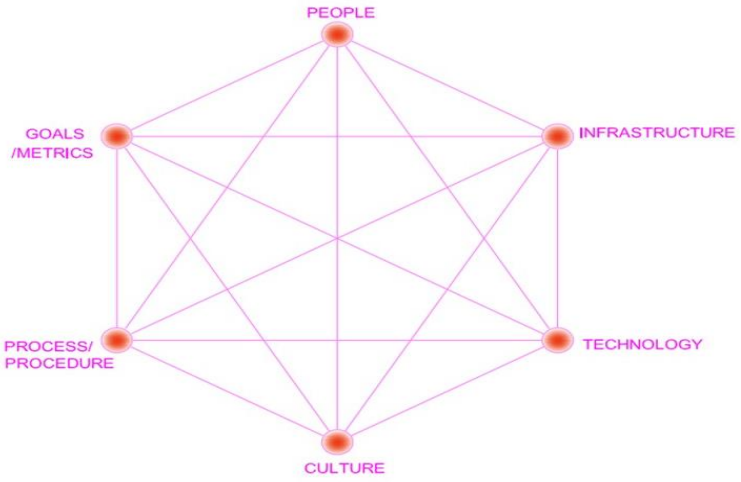

Fig. 02 Socio-technical Theory System (Source: Author)

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Therefore, it is now abundantly clear thanks to the previous analytical study of smart materials, structures, and systems that smart materials technologies will be the primary factor directly influencing all design processes, from the initial concept in an innovative design paradigm to the completion of the building. The ability of architects to survive depends on their constant desire to innovate. The recommended design paradigm is produced as a result of this and the socio-technical objectives and is shown in Fig. 3.

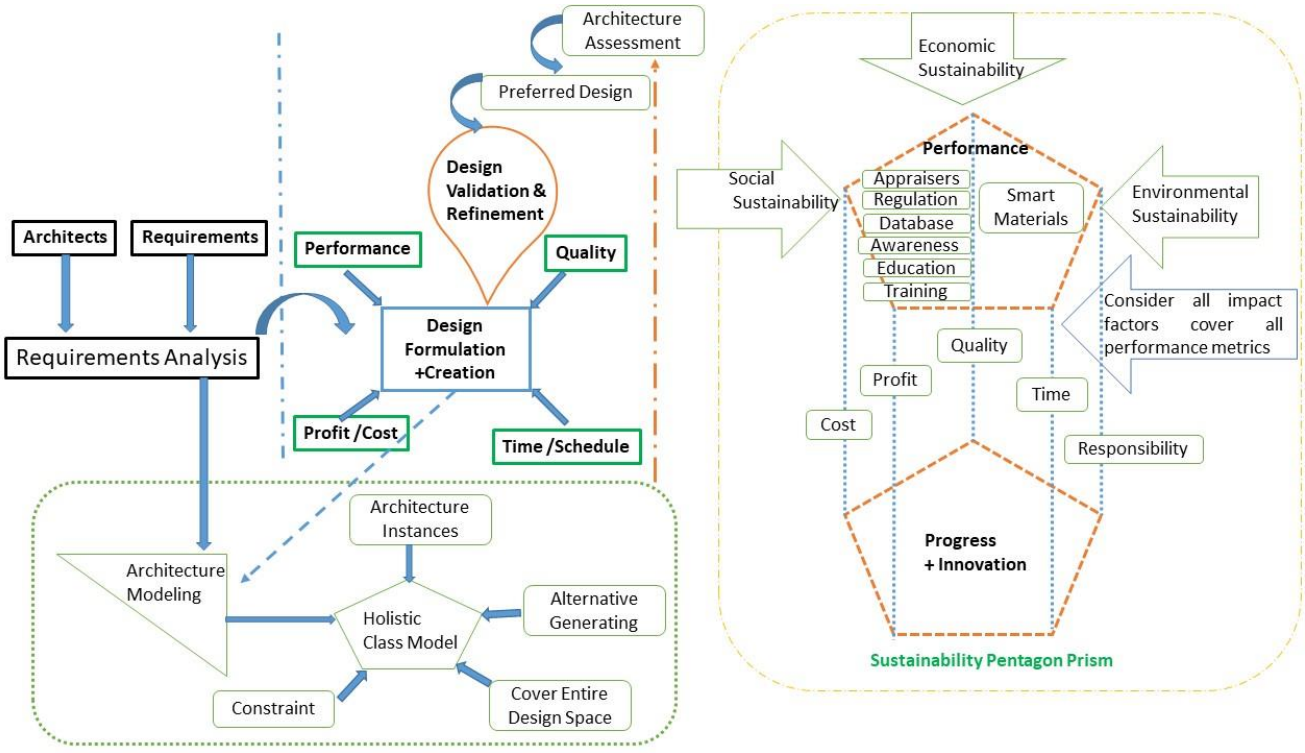

Fig. -03 Framework for Innovative Architectural Design Built Form with Smart Materials
(Source: Author)

6. CONCLUSION

The material is exposed and felt throughout the whole depth of the construction, not only as a texture or surface. Consequently, material should be viewed by architects as a functional element with behavior that might be morphic, adaptable, and efficient throughout each step of design operation.The twenty-first century has brought about a time of urgent environmental risks, increasing energy prices, and a firming conviction that sustainable architecture design may produce significant improvements in general quality of life and long-term resource preservation. The expanding selection of clean technology goods and procedures that not only promote sustainable concepts but also do so financially underpins all of this. The development of smart materials has the potential to significantly increase sustainability(Miranda, 2019). The adoption of smart materials innovation is hampered by a number of factors, including cost, liability, market cycles, and the unreliability of some products. Additionally, there is a lack of coherence and consistency in the way success is measured, particularly when it comes to the verification and endorsement of new technology.

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The relationship between architecture and building materials, structures, and systems is correlated, compound, interactive, and complicated. This connection became a crucial factor in the development of creative architectural design. As new intelligent materials begin to arise in the area of architecture, they emphasize this design philosophy and present us with fresh opportunities and possibilities that have the power to change the way we approach.

Technology has also come into use much later with this growing era. In today's time, technology can do what we never thought possible and it is so beneficial that it does not change anything in the design and it is not visible to anyone, instead of being its physical manifestation. However, all materials are far above our reach in the present time but also those available one material can be extended beyond the quickness and efficiency. Smart materials and sustainable technologies should be infused with the construction and Architectural processes(D. Michelle Addington Daniel L. Schodek Harvard, 2005). These will be helpful for making the coherent designed spaces. As smart materials and sustainable technologies used, then the sense of belonging for the visitors will be created and user can belong him to the spaces. Today's use of smart materials also maintains the privacy and quality of life for the residents/users. This approach of design can help accentuate the quality of livability Design. While increasing the demand for the development and enriching the local area and context. An integrated approach towards a new innovative architectural design framework has been proposed with respect to claims smart materials (As shown in Fig.03).

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