International Journal of Trend in Scientific Research and Development (IJTSRD)
Volume 10 Issue 4, Jul-Aug 2026 Available Online: www.ijtsrd.com e-ISSN: 2456 – 6470

Building Information Modeling in Smart Cities

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ABSTRACT

The world is urbanizing at a historic pace. By 2040, an estimated 70% of the global population will reside in urban environments, placing extraordinary pressure on infrastructure, governance, and natural resources. In response, the concept of the "smart city" has gained prominence as an urban development model that leverages information and communication technology (ICT) to enhance sustainability, efficiency, and quality of life. The evolution of smart cities is transforming how we live, work, and interact with urban environments. Central to this transformation of smart cities is building information modeling (BIM). BIM is a digital methodology that creates a multidimensional, data-rich representation of a building or infrastructure asset. It has evolved into a comprehensive knowledge management platform that supports the entire lifecycle of urban infrastructure - from initial planning and design through construction, operation, and eventual decommissioning. This paper explores the transformative role of BIM in smart cities.

KEYWORDS: *building information modeling (BIM), smart cities.*

How to cite this paper: Matthew N. O. Sadiku | Paul A. Adekunte | Janet O. Sadiku "Building Information Modeling in Smart Cities" Published in International Journal of Trend in Scientific Research and Development (ijtsrd), ISSN: 2456-6470, Volume-10 | Issue-4, August 2026, pp.917-926, URL: www.ijtsrd.com/papers/ijtsrd141950.pdf

IJTSRD141950

INTRODUCTION

The rapid expansion of urban populations presents significant challenges, including resource depletion, environmental degradation, and the strain on existing infrastructure. In response, the concept of the "smart city" has emerged as a paradigm to enhance urban sustainability, efficiency, and the quality of life for residents. As urbanization accelerates and cities face unprecedented challenges in sustainability, resource management, and livability, the integration of advanced digital technologies has become imperative. Building information modeling (BIM), traditionally a tool for the architecture, engineering, and construction (AEC) industry, has evolved into a foundational pillar for the development of smart cities. BIM facilitates sustainable urban planning, intelligent infrastructure management, and the creation of urban digital twins. Today, BIM is recognized as a critical catalyst in the smart city ecosystem, extending its capabilities from single structures to the broader urban landscape [1].

BIM constitutes a digital representation encompassing both the physical infrastructure and functional characteristics of a structure. It is a process that involves the generation and management of digital representations of physical and functional characteristics of places. It serves as a dependable cornerstone for information modeling, functioning as a communal knowledge repository for facility information across its entire life cycle. The development of smart city projects and services, as well as the integration and application of BIM technologies, cannot be separated from the sustainable environment, which has a positive impact on sustainable development to achieve the SDGs. Due to the widespread adoption of cutting-edge technologies such as BIM, the services offered by cities have expanded as studies have continued to grow with respect to smart cities. The combination of the smart city paradigm with BIM is currently regarded as a successful way to reduce emissions, go green, and cut costs, which has benefited the growth of the market and the industry [2].

BACKGROUND ON BUILDING INFORMATION MODELING

Building information modeling (BIM) is a digital representation of physical and functional characteristics of a facility. It is the holistic process of creating and managing information for a built asset. BIM is a digital representation of the physical and functional characteristics of a building or facility. The representation can be used to simulate the construction and operation of the facility, and to provide information for decision-making throughout the project lifecycle.

Building information models (BIMs) are computer files (often but not always in proprietary formats and containing proprietary data) which can be extracted, exchanged or networked to support decision-making regarding a built asset. The main objective of creating the models is to provide builders with all relevant information about the project in a digital format. BIM software (such as Revit, Microstation, Vectorworks, Infraworks, ArchiCAD, BIM 360, Formit, Civil 3D, GBS Tekla, etc.) allows the design team on a project to construct a 3D model that represents the one we intend to build. Two typical examples of 3D models used in BIM are presented in Figure 1 [3] and Figure 2 [4]. The BIM software is used by individuals, businesses and government agencies who plan, design, construct, operate and maintain buildings and diverse physical infrastructures, such as water, refuse, electricity, gas, communication utilities, roads, railways, bridges, ports and tunnels. The BIM concept envisages virtual construction of a facility prior to its actual physical construction, in order to reduce uncertainty, improve safety, work out problems, and simulate and analyze potential impacts. However, the use of BIM goes beyond the planning and design phase of a project, extending throughout the life cycle of the asset [5]. Figure 3 shows various components of BIM [6].

Though the ‘B’ in BIM stands for building, it covers all constructions in the AEC industry, from residential and industrial buildings to bridges and roads. The ‘I’ in BIM stands for information, referring to the integrated information within BIM models. This is its core concept - information, parameters, attributes, whatever we call it. The ‘M’ in BIM stands for modelling. BIM models are known to be condensed with data. Thus, BIM is not a type of software, but a holistic process for managing the building information. We use software and tools that aid the BIM process. BIM covers the entire cycle of the building, from design development to post-construction maintenance. It includes planning, designing, construction, and even operations [7].

AEC professionals relied on manual drawings for decades until CAD came into existence. Traditional building design was largely reliant upon two-dimensional technical drawings (plans, elevations, sections, etc.). Building information modeling extends the three primary spatial dimensions (width, height and depth). The model can contain all the physical and functional characteristics of a project, including structure, geometry, aesthetics, materials, systems, and dynamic performance. A 3D model becomes 4D if a time component is added, and 5D when cost-related information is included. BIM enables a virtual information model to be shared by the design team (architects, landscape architects, surveyors, civil, structural and building services engineers, etc.), the main contractor and subcontractors, and the owner/operator. It enables all the stakeholders to use the same shared 3D model, from architects to surveyors, engineers, contractors, to building owners. This allows everyone to have access to the relevant information at the right moment during the design and construction of a project.

The concept of BIM has existed since the 1970s, when architects and engineers began to explore the use of computer-aided design (CAD) software to create 3D models of buildings. The terms “Building Information Model” or “Building Information Management,” and “Building Information Modeling” did not become popularly used until some 10 years later. BIM only became an agreed term in the early 2000s. BIM has evolved over the past few decades from simple 2D drafting to sophisticated 3D modeling with rich data integration. Figure 4 shows early developments of BIM [8]. Today, BIM is an essential tool for the AEC industry. It is used throughout the entire project lifecycle, from design and construction to operation and maintenance.

A comprehensive BIM modeling solution combines the major elements of building information modeling software, data repository, collaboration, analysis, visualization, and project management tools [4]. Different levels of BIM can be achieved for various types of projects**.** Below are brief descriptions of the levels [9]:

Level 0 BIM: Paper-based drawings + zero collaboration

Level 1 BIM: 2D construction drawings + some 3D modeling

Level 2 BIM: Teams work in their own 3D models

Level 3 BIM: Teams work with a shared 3D model

Level 4 BIM: Incorporating time-related data into the BIM model

Level 5 BIM: Integrating cost estimation and management within the BIM model

Level 6 BIM: Including sustainability data

Level 7 BIM: Used to manage and maintain facilities

Building information modeling (BIM) is a smart, model-based process that helps everyone involved in a building project - from architects and engineers to contractors and facility managers - work together using one shared digital model. BIM evolves through multiple dimensions [10]:

- 3D: Geometric representation
- 4D: Time scheduling
- 5D: Cost estimation
- 6D: Facility management information
- 7D: Environmental and energy performance data

This is illustrated in Figure 5 [11].

BIM IN SMART CITIES

The rapid urbanization of the 21st century has necessitated a paradigm shift in how cities are planned, constructed, and managed. Smart cities are a response to the challenges posed by urbanization, the digital revolution, and society's demand for more efficient and sustainable urban services, aiming to enhance the quality of life. Driven by the integration of digital technologies and urban infrastructure, smart cities aim to enhance sustainability, efficiency, and the overall quality of life for residents. Central to the realization of smart cities is building information modeling (BIM), a digital representation process that has evolved from individual building design to encompass city-wide infrastructure management. Today, BIM provides a data-rich, collaborative environment that integrates physical and functional characteristics of assets across their entire lifecycle, making it an indispensable tool for smart city development [1]. Figure 6 shows a typical smart city [12], while Figure 7 illustrates the role of BIM in smart cities [13].

APPLICATION OF BIM IN SMART CITIES

The integration of BIM into smart city initiatives revolutionizes how urban environments are planned, developed, and maintained. Its applications span multiple domains, contributing significantly to the overarching goals of urban sustainability and resilience. Common applications of BIM in smart cities include the following [1,2,14]:

- *Urban Planning*: BIM enables a paradigm shift from traditional, disconnected planning processes to a centralized, data-driven approach. Urban planners can simulate, analyze, and visualize developments before physical construction begins. By evaluating factors such as sunlight exposure, wind circulation, and energy consumption, BIM facilitates the design of energy-efficient and environmentally responsive structures.
- *Facility Management*: The efficient management of public assets-such as roads, bridges, transit hubs, and utility networks-is a cornerstone of smart city operations. BIM provides a centralized repository of data that tracks an asset from its conceptual design through construction, operation, and eventual decommissioning. The true potential of BIM in facility management is unlocked when integrated with the Internet of things (IoT). Sensors embedded in physical infrastructure feed real-time data back into the BIM model.
- *Asset Management*: In a smart city, the continuous monitoring and management of public assets-such as roads, bridges, and utility networks-are vital. Post-construction, a BIM model serves as a "living document" that stores comprehensive information about materials, systems, and maintenance histories. When integrated with IoT sensors, these models can track real-time performance data, predict wear and tear, and optimize maintenance schedules, thereby reducing long-term operational costs and extending the lifespan of urban infrastructure.
- *Disaster Management:* Urban areas are increasingly vulnerable to natural and human-made disasters. BIM, particularly when integrated with GIS, significantly enhances a city's disaster management capabilities across prevention, response, and recovery phases. BIM-GIS integration allows for the creation of highly accurate 3D urban models to simulate disaster scenarios, such as flooding or earthquakes. This helps authorities identify high-risk zones and evaluate the structural resilience of existing buildings. During a crisis, real-time data from BIM models, combined with smart building technologies, can guide emergency responders by providing detailed internal layouts of buildings, identifying hazardous materials, and tracking the movement of evacuees.
- *City Information Modeling* (CIM): As urban environments become more complex, the application of BIM has expanded beyond individual structures to encompass entire urban landscapes, a concept increasingly referred to as City Information Modeling (CIM). The amalgamation of BIM, GIS, and IoT data culminates in City Information Modeling (CIM). CIM represents a multi-scale, semantically

interoperable digital platform that scales the principles of BIM to the city level. CIM serves as the foundational data framework for creating an "urban digital twin"-a virtual, real-time replica of the physical city. CIM integrates BIM data with macro-level urban data, providing a holistic view of the city. This evolution allows urban planners to design cities more intelligently, optimizing the distribution of resources, infrastructure, and services.

- *Transportation*: Transportation networks are the arteries of a smart city. BIM supports the development of intelligent transportation systems by providing accurate digital models of road networks, railways, and transit stations. Planners use these models to evaluate traffic patterns, simulate pedestrian flow, and design multi-modal transit hubs that reduce congestion and lower carbon emissions. Figure 8 shows transportation in a smart city [15].
- *Smart Tourism*: As the foundational technology for the growth of smart tourism in tourist places, BIM digital technology has become a crucial component of the business models to tourism organizations, which gives smartphone users assistance and services through a variety of applications. The application of BIM technologies in the field of smart tourism provides inspiration for city management, such as public institutions and local governments. For example, the integration of BIM and GIS for the 3D modeling of cities provides an efficient way to share information and knowledge about architectural heritage to city managers involved in decision-making processes and territorial management. In addition, business models in the context of tourism services usually refer to modern technologies that create value through the use of digital technologies.
- *Digital Twins:* Urban digital twins (UDTs) represent a paradigm shift in city management. They allow city administrators to conduct extensive analyses and simulations. Decision-makers can test the impact of policy changes, infrastructure investments, or emergency response plans in the virtual environment before implementing them in the real world. A prominent real-world example is Virtual Singapore, a dynamic 3D city model and collaborative data platform. Developed using high-resolution topographical data and integrating real-time sensor feeds, Virtual Singapore enables stakeholders to test-bed solutions for urban planning, environmental sustainability, and disaster management in a risk-free digital space.
- *Immersive Technologies*: Immersive technology specifically refers to technologies that immerse users in the virtual environment, including virtual reality (VR), augmented reality (AR), and mixed reality (MR). There is a gradual integration of BIM and immersive technology, as well as the promotion of sustainable smart cities, such as AR, tourism, visualization, VR, construction projects, energy consumption, interoperability, cloud, environmental impact, heritage building information modeling, and lifecycle assessment. VR is the most prevalent immersive technology used in research associated with sustainable energy performance, cultural heritage preservation, intelligent construction engineering management, facility management, sustainable engineering education, and public services of smart cities (specifically transportation and tourism). Immersive technology, particularly AR, plays a role in promoting energy conservation and sustainability in smart cities. Additionally, immersive technology enhances tourism experiences and cultural heritage understanding in sustainable smart cities, benefiting citizens of all ages.
- *BIM-GIS Integration:* To achieve a holistic smart city framework, BIM must be integrated with Geographic Information Systems (GIS). GIS maps spatial relationships and geographic data on a macro level. The integration of BIM and GIS bridges the gap between the design world and the geospatial world. This synergy allows planners to place detailed building models within their exact geographical context, facilitating advanced site analysis, flood risk assessment, and transportation planning. The combination of BIM and GIS supports a wide range of smart city applications, including the planning of utility infrastructure, the assessment of environmental impacts, and the optimization of transportation networks. This integration empowers planners to make smarter engineering decisions, provides situational awareness that increases safety, and identifies patterns that improve public health and commerce. For example, planners can evaluate how a new high-rise development will impact local traffic patterns or underground utility networks.

BENEFITS

AI algorithms can process the massive datasets generated by CIM to uncover patterns and optimize decision-making. Other benefits of BIM in smart cities include the following [1,13]:

- *Economic Efficiency*: The aggregate financial impact of BIM adoption is substantial. The financial implications of urban infrastructure projects are immense, and cost overruns have long been a systemic challenge in the construction industry. BIM introduces measurable economic efficiencies across the entire project lifecycle, from initial design through long-term operations and maintenance. Beyond the construction phase, 7D BIM delivers sustained economic value through optimized facility management.

- *Energy Efficiency*: Sustainability is a primary objective of smart cities, and BIM plays a crucial role in optimizing resource utilization. Through detailed energy modeling, BIM evaluates building performance regarding heating, ventilation, air conditioning (HVAC) efficiency, and overall energy demand. At the city scale, this allows municipalities to forecast energy and water requirements, optimize waste management routes, and design infrastructure that minimizes the urban carbon footprint.

- *Lifecycle Management*: BIM supports the entire lifecycle of urban infrastructure, from design and construction to operation and maintenance. In a smart city, this lifecycle approach ensures that buildings, roads, bridges, and public utilities are not only efficiently built but also sustainably managed over time.

- *Integration:* One of the most critical aspects of smart cities is the interconnectedness of systems. BIM facilitates real-time collaboration among stakeholders from various sectors such as transportation, utilities, and telecommunications. This integration ensures that all components of a smart city can function in harmony.

- *Collaboration*: The planning and management of a smart city involves an extraordinarily diverse array of stakeholders: architects, engineers, contractors, utility providers, municipal authorities, and the citizens themselves. By consolidating all project data - architectural, structural, mechanical, electrical, and plumbing - into a single, accessible model, BIM eliminates the information silos that have long plagued the construction and urban management industries. All stakeholders can access the same up-to-date information in real-time, reducing misunderstandings, minimizing errors, and ensuring that every voice contributes meaningfully to the decision-making process. This collaborative environment is particularly valuable in the context of smart city governance, where decisions about infrastructure investments have far-reaching social, economic, and environmental consequences.

- *Sustainability:* A primary objective of smart cities is sustainability, aligning with the United Nations Sustainable Development Goals (SDGs). One of the most significant benefits of BIM in smart cities is its capacity to drive sustainable urban planning. Traditional planning processes have historically relied on disconnected, two-dimensional representations that fail to capture the complex interplay between new developments and existing infrastructure. BIM facilitates sustainable urban planning by allowing designers and planners to simulate and analyze the environmental impact of proposed developments before physical construction begins. BIM tools enable precise calculations of energy, water, and material requirements, helping planners optimize resource consumption and reduce waste. A compelling illustration of BIM-enabled sustainable planning is found in Amsterdam, which has utilized City Information Modeling (CIM) - an urban-scale extension of BIM - to incorporate environmental data such as solar potential and flood risk analysis into its urban design process.

CHALLENGES

In spite of its vast potential, the widespread adoption of BIM in smart city development faces several significant challenges. Challenges related to interoperability, high initial costs, skills gap, cybersecurity, software incompatibility, and interoperability remain. The biggest challenge is the defect of BIM in scalability, interoperability, and remote collaboration. Addressing these challenges is not solely a technological endeavor but a socio-technical transformation. Other challenges of BIM in smart cities include the following [1]:

- *High Initial Costs:* The development of comprehensive BIM models and urban digital twins requires substantial upfront investment. The costs associated with data collection (e.g., aerial LiDAR, mobile mapping), software licensing, and establishing the necessary IT infrastructure can be prohibitive for many municipalities.

- *Interoperability*: One of the primary technical hurdles is interoperability-the ability of different software systems and platforms to exchange and utilize data seamlessly. Integrating data from diverse stakeholders, software platforms, and legacy systems remains a major technical hurdle.

BIM and GIS traditionally use different data formats. Overcoming this requires the adoption of open data standards, such as Industry Foundation Classes (IFC) and CityGML, to ensure reliable data exchange without vendor lock-in.

- *Skills Gap*: The successful implementation of BIM in smart cities is fundamentally dependent on human capital. However, there is a widespread shortage of professionals equipped with the specialized technical skills required to manage and analyze complex BIM and CIM data. Furthermore, fragmented governmental structures and a lack of collaborative policy frameworks often hinder the cross-departmental data sharing necessary for smart city initiatives.
- *Cybersecurity:* As smart cities rely increasingly on shared data, security, privacy, and trust become paramount. As cities become more digitized and reliant on interconnected models, ensuring the cybersecurity of critical infrastructure data becomes paramount. As BIM models become integrated into smart city networks, they store sensitive infrastructural data, including security layouts, energy grids, and surveillance systems. Protecting these interconnected digital twins from cyber threats is paramount. The lack of standardized cybersecurity protocols specifically tailored for BIM and UDT environments leaves urban infrastructure vulnerable to malicious attacks.
- *Scalability:* Urban digital twins require processing massive volumes of real-time data. BIM models are inherently data-heavy; scaling this level of detail to an entire city can overwhelm computational resources and storage capacities. Managing the lifecycle of this data-ensuring it remains accurate, updated, and secure over decades-poses a continuous technical and logistical challenge for municipal authorities.
- *Governance:* Perhaps the most complex, yet least explored, challenges are those related to governance, policy, and institutional frameworks. BIM is not merely a technical tool but an urban governance infrastructure that requires regulatory clarity and cross-agency coordination. Urban governance typically involves multiple fragmented departments-such as transport, energy, planning, and public works-each operating in silos with proprietary data systems. BIM requires a collaborative, integrated approach that contradicts traditional bureaucratic structures.
- *Developing Countries*: The economic challenges are acutely felt in developing countries. Research indicates that financial constraints, coupled with a lack of technological infrastructure, significantly hinder BIM adoption in regions such as Africa and parts of Asia. In these contexts, the focus remains on addressing basic infrastructural deficits, making advanced digital tools like BIM appear as secondary priorities.

FUTURE OF BIM IN SMART CITIES

The future of BIM lies in its transition from isolated building models to interconnected city information modeling (CIM) and urban digital twins, ultimately driving sustainable, resilient, and intelligent urban ecosystems. The most critical step toward CIM is the seamless integration of BIM with geographic information systems (GIS). While BIM provides semantic, object-oriented data about building components, GIS offers the spatial and geospatial context of the broader urban environment. The ultimate manifestation of CIM is the urban digital twin.

The future of BIM in smart cities is intrinsically linked to its expansion in scale. While BIM excels at the micro-level (individual structures), smart cities require macro-level intelligence. The future is closely tied to advancements in emerging technologies such as geographic information systems (GIS), the Internet of things (IoT), artificial intelligence (AI), digital twins, and blockchain. BIM is expected to evolve further with the integration of these technologies. The integration of artificial intelligence (AI) and machine learning (ML) with BIM will automate complex design processes, optimize urban layouts, and provide deeper predictive insights from urban data. The full transformative potential of BIM in smart cities is realized through its convergence with a suite of emerging technologies. As urbanization continues, the transition from isolated building models to interconnected, intelligent urban ecosystems will be essential. The future lies in generative design, where AI uses BIM parameters to automatically generate thousands of optimized architectural and urban layouts based on specific constraints [1].

CONCLUSION

Building information modeling has transcended its origins in the construction industry to become an indispensable mechanism for smart city development. The integration of BIM into the development of smart cities represents a paradigm shift in urban planning, governance, and infrastructure management. BIM is no longer just a tool for architects and engineers; it is a foundational technology for the future of urban development. Its application has expanded to the urban scale, forming the foundation of city information modeling (CIM) and urban digital twins

(UDTs). By providing a data-rich, lifecycle-oriented approach to urban assets, BIM enables sustainable planning, efficient resource management, and the creation of dynamic urban digital twins.

As global urbanization accelerates, the strategic application of BIM will be essential in shaping cities that can meet the complex environmental and social demands of the future. Ultimately, the strategic implementation of BIM is not merely a technological upgrade, but a fundamental shift towards shaping the sustainable, intelligent cities of tomorrow. More information on BIM in smart cities is available from the book in [16] and in the following related journals:

- Construction Magazine
- Buildings
- Journal of Building Engineering
- Journal of Construction Engineering and Management
- WIT Transactions on The Built Environment

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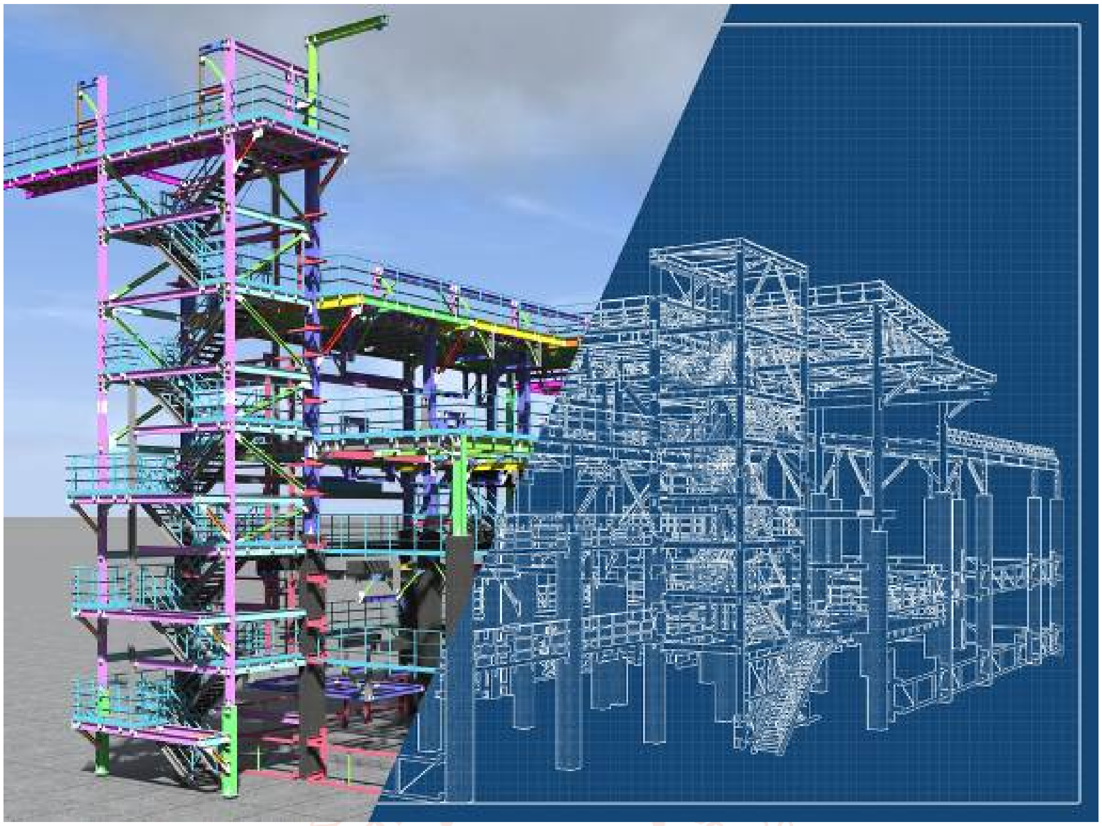

Figure 1 A typical 3D model used in BIM [3].

Figure 2 Another example of 3D model used in BIM [4].

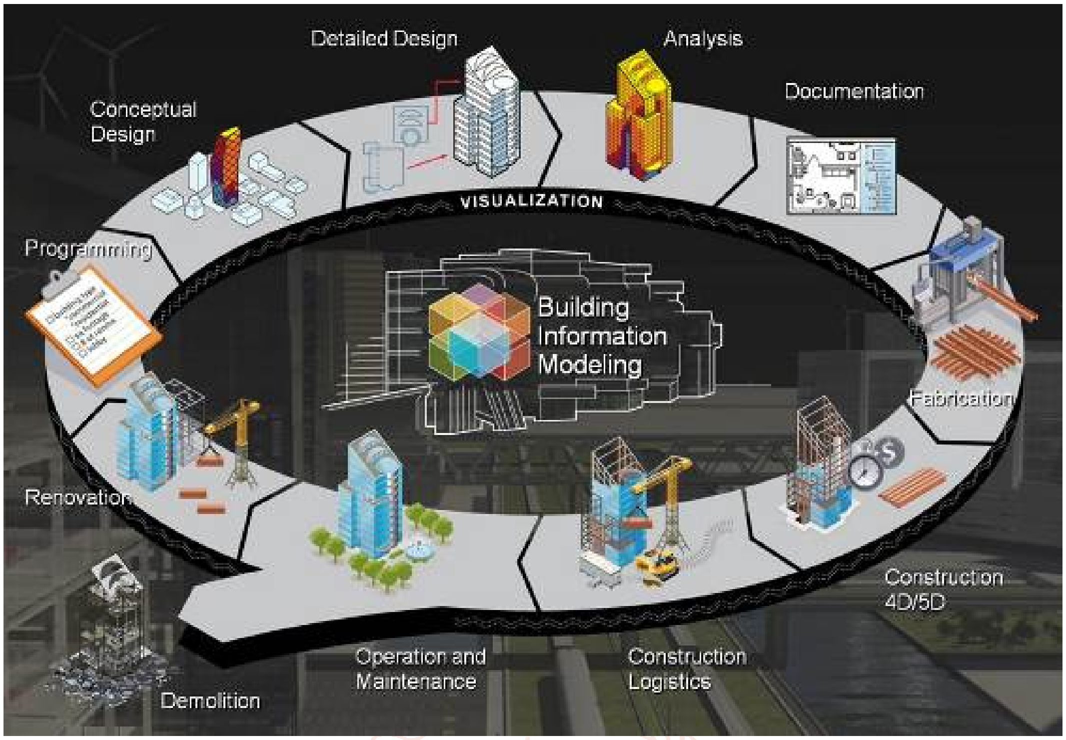

Figure 3 Various components of BIM [6].

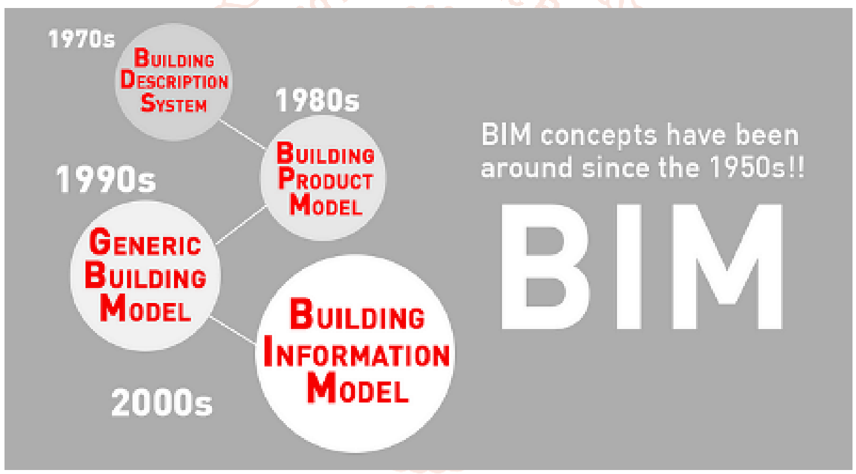

Figure 4 Early developments of BIM [7].

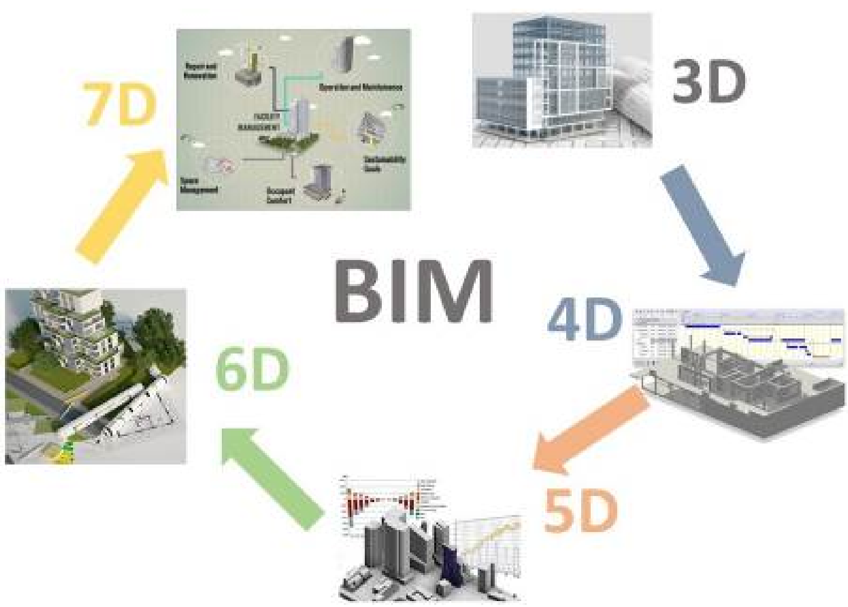

Figure 5 BIM evolves through multiple dimensions [11].

Figure 6 A typical smart city [12].

Figure 7 The role of BIM in smart cities [13].

Figure 8 Transportation in a smart city [15].