# POLITECNICO DI MILANO

## Master in

Building Information Modelling

European Master in
Building Information Modelling

# CIM The application of City Information Modelling


Supervisor:

Ing. Alessandro Zichi

Author:

Hashir Usman



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# STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of ethics and conduct of Politecnico di Milano.

# SOMMARIO

Le città stanno diventando sostanzialmente attraenti per i cittadini alla ricerca di una migliore qualità della vita; questo fenomeno sta stimolando un grande afflusso in direzione delle città. La fornitura di pianificazione urbana contemporanea, la gestione ed i meccanismi di monitoraggio sono insufficienti per supportare uno sviluppo urbano sostenibile e questa situazione si sta esacerbando a causa dei cambiamenti climatici. Sono stati proposti molti strumenti e strategie nel tentativo di spingere le città verso uno sviluppo urbano sostenibile. Le Nazioni Unite hanno presentato una strategia per lo sviluppo urbano sostenibile nelle città, attraverso la definizione dell'"Obiettivo di Sviluppo sostenibile 11" (SDG 11). Altre organizzazioni, come LEED, offrono il proprio sistema di valutazione della sostenibilità della città, allineato con l'SDG 11, per valutare e dimostrare le prestazioni di sostenibilità di una città. Anche modellazione delle informazioni sulla città (CIM) è stato sviluppato al fine di gestire efficacemente una città e supportare il processo decisionale evidence-based. Si tratta di un modello 3D di una città, che è in grado di facilitare l'effettivo coinvolgimento delle parti interessate grazie ai suoi aspetti di visualizzazione e alla capacità di eseguire analisi come il potenziale di energia solare, la mappatura dell'inquinamento acustico, ecc. CIM è stato testato ed implementato da molte città in tutto il mondo. Tuttavia, l'indagine basata sulla sostenibilità delle applicazioni di CIM è ancora limitata per quanto riguarda la ricerca, in particolare la valutazione dei parametri LEED. Questa tesi si concentra sulla conduzione di una valutazione dettagliata e all'avanguardia dei parametri di sostenibilità di LEED; l'obiettivo è quello di esplorare come CIM può facilitare la valutazione, la manifestazione e l'accelerazione dello sviluppo urbano sostenibile. È stata proposta una tassonomia per i modelli 3D delle città, sulla base dell'approccio di raccolta e modellazione dei dati, ovvero la modellazione statica 3D e la modellazione dinamica 3D. I parametri di sostenibilità LEED sono stati identificati e distinti in base alla tassonomia proposta, che incorpora gli elementi e le componenti della città da considerare per le valutazioni di sostenibilità. Inoltre, è stato proposto un quadro per sviluppare il gemello digitale di una città costruita utilizzando la struttura CIM.

**Parole chiave:** (3D modellazione della città, modellazione delle informazioni sulla città, gemello digitale, LEED, sviluppo urbano sostenibile)

# ABSTRACT

Cities are becoming substantially appealing for masses in the pursuit of a better life which is spurring a large influx of population into cities. The provision of contemporary city planning, management, and monitoring mechanisms are insufficient to underpin sustainable urban development and this situation is getting exacerbated due to climate change. Many tools and strategies have been propounded in the bid to push cities towards sustainable urban development. The United Nations has presented a strategy for sustainable urban development in cities under the sustainable development goal 11 (SDG 11). Other organizations such as LEED proffer their city sustainability rating system aligned with SDG 11 to evaluate and demonstrate the sustainability performance of a city. City Information Modelling (CIM) is also developed to effectively manage a city and support evidence-based decision-making. It involves information-enriched 3D modelling of a city that is capable of facilitating the effective involvement of stakeholders due to its visualization aspects and capacity of performing analysis such as solar energy potential, noise pollution mapping, etc. CIM has been explored and implemented by many cities around the world. However, sustainability-based investigation of CIM applications is still limited in research especially the evaluation of LEED parameters with the application of CIM. This thesis focuses on conducting a state-of-art detailed assessment of sustainability parameters of LEED aligned with the capabilities of CIM to explore how CIM application can facilitate to evaluate, manifest, and accelerate sustainable urban development. A taxonomy has been proposed for 3D city modelling based on data collection and modelling approach i.e., static 3D city modelling and dynamic 3D city modelling. LEED sustainability parameters have been identified and distinguished based on the proposed taxonomy which incorporates the city elements and components to be considered for sustainability assessments. Furthermore, a framework has been propounded to develop the digital twin of a city built on the CIM structure.

**Keywords:** (3D City Modelling, City Information Modelling, Digital Twin, LEED, Sustainable Urban Development)

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# 1. INTRODUCTION

According to the United Nations, around 55% of the total population of the world has been settled in urban areas and this share is expected to rise to 68% by 2050 (*68% of the world population projected to live in urban areas by 2050, says UN | UN DESA | United Nations Department of Economic and Social Affairs*, no date). Cities being the hub of economic activity attract masses to swarm towards urban areas in search of a better life (*Cities in the World: A New Perspective on Urbanisation*, 2020). To cope up with the needs of the urban population efficiently is getting demanding with every passing day. The fissure between effective or desired planning and management and actual planning and management of cities is getting wider and wider. Therefore, the issues cities are facing and the approaches to address them have become a hot topic nowadays (Man Li *et al.*, 2021). According to the World Economic Forum, the cities are striving against 5 major problems including environmental issues, provision of adequate resources, inequality and financial disparities between the inhabitants, technological divide, lack of potent government (*Five big challenges facing big cities of the future | World Economic Forum*, no date).

Cities are the core of major economic activity, innovation, progress, prosperity, creativity, social integration, educational and health facilities, infrastructure, cultural representation, and diversity (*CITIES AS INNOVATION HUBS*, 2017). To harness all these benefits and opportunities, cities need to sustain themselves and their population with the additional ability to address the needs of future urban citizens. It is possible if urban sustainability frameworks are being followed for the planning and management of the city. The linkage between rural and urban areas needs to be strengthened in the bid to nourish the relationship between social, economic, and environmental aspects of the cities (*68% of the world population projected to live in urban areas by 2050, says UN | UN DESA | United Nations Department of Economic and Social Affairs*, no date). Various organizations have presented different frameworks for sustainable urban development with the United Nations being the most prevalent one. The United Nations has published a list of 17 sustainable development goals (SDGs) and the 11th SDG targets urban areas. The purpose of this goal is to make cities and urban settlements inclusive, safe, resilient, and sustainable (*Goal 11 | Department of Economic and Social Affairs*, no date). Besides the United Nations, many other organizations have also focused on sustainable urban development and compiled a list of measurable performance parameters to calculate the extent of sustainable development in a city or community. The Leadership in Energy and Environmental Design (LEED) is a Green Building Rating System initiated by the U.S. Green Building Council (USGBC) to provide a set of standards for sustainable and environment-friendly planning, design, construction, and operation of buildings and neighbourhoods (*LEED: Past, present and future | U.S. Green Building Council*, no date). Similarly, Building Research Establishment Environmental Assessment Method (BREEAM) was launched in 1990 as an assessment tool for the environmental performance of new building designs (*Introduction*, no date a). Both of these assessment authorities provide certifications based on performance scores earned by a detailed assessment of specific parameters. LEED and BREEAM both expanded their assessment approaches from examination of building parameters to investigate the extent of sustainability in cities and communities, viz. LEED for cities and communities and BREEAM communities.

City systems are quite complex and integrated where services and utilities are entangled. Previously, city planning, development and management were handled by only a handful of entities and professionals who were working independently, however, currently, the city-systems are so integrated that a large number of stakeholders are involved and collaborating closely in city planning and management (Geertman and Stillwell, 2003). For better management of cities, different tools and technologies have been recommended and employed in the cities. One of those tools is City information Modelling (CIM) which is the digital representation of a city (Dantas, Sousa, and Melo, 2019). CIM involves creating a virtual 3D representation to mirror the features of the city such as buildings, streets, and other city elements and structures into a digital platform (Biljecki *et al.*, 2015). Visual representation enables better awareness of the city infrastructure, enhanced engagement of stakeholders, impact estimation of any intervention and informed decision-making (Ross, 2010). CIM acts as a digital instrument for urban planning with the compilation of heterogeneous data and information related to a myriad of city services, processes, and utilities to nourish improved decision-making to transform the city into a smart and resilient city (Furjani *et al.*, 2020). 3D city information models have been widely used for various purposes such as city planning, tourism, disaster management, simulations for training and gaming, and many other purposes (*3D City Model of New York City - Lehrstuhl für Geoinformatik*, no date a). 3D city models target a broad range of applications and use cases, however, the complete scope of the application of CIM has not been explored yet (Biljecki *et al.*, 2015).

### 1.1. Research problem and motivation:

It has been noticed in the research review that the relationship of CIM with sustainable urban development has not been properly explored yet in terms of determining the capability of CIM to measure the extent of sustainability in a city especially the parameters of LEED and BREEAM. As stated above, cities are complex socio-economic hubs where the city systems, elements, materials, assets, infrastructure, services, and people are entangled and this fusion can act as a catalyst for development on all fronts of the society, yet it creates a lot of hurdles in city planning and management due to lack of evidence-based decision making, sufficient information, overarching monitoring mechanism, effective scenario predictions, suitable protocols to tackle challenges, etc. which arise due to absence of a decision support tool. Also, there is a lack of an all-embracing framework that encompasses all the spheres of the city including the environment, society, and economy which are vital for sustainable urban development. Therefore, it will be assessed in this study that if CIM is the right tool to evaluate and underpin sustainability in a city.

### 1.2. Research objectives and method:

Since CIM has not been analysed comprehensively by taking into consideration the sustainable urban development parameters. The purpose of this research is to address this gap in the literature by aligning the applications of CIM with sustainable urban development and propose a state-of-the-art CIM applicability framework in this study. A thorough analysis of CIM applications will be conducted to examine its utilization in the domain of sustainable urban development by evaluating its consistency in examining LEED performance at a city scale which, in turn, indicates the level of sustainable development in an urban context. It will be carried out by evaluating LEED for cities and communities' categories and parameters individually with the implementation of CIM to determine if CIM is an essential key for cities' sustainability monitoring, management, and augmentation. The city elements and infrastructure will be focused which are critical in overarching monitoring and decision-making to aid decision-makers, actors, and stakeholders. It will involve the development of a taxonomy for CIM based on its data collection infrastructure and approach. Also, a framework for developing a CIM-enabled digital twin of a city in different layers to accelerate sustainable urban development will be presented.

### 1.3. Thesis structure:

The thesis is divided into 5 different chapters. Chapter 1 includes the introduction, research problem and motivation, research objectives and methodology, and thesis structure. A literature review is involved in chapter 2 which contains information about city information modelling, building information modelling, international exchange standards of CIM and BIM, viz. CityGML and IFC, CIM in sustainable urban development perspective, common CIM applications, types of CIM models, digital twin, and some case studies. Chapter 3 includes the main research part with elaborated methodology, detailed analysis of LEED for cities and communities based on CIM applicability, development of a CIM taxonomy. Chapter 4 incorporates the development of a proposed framework for CIM and digital twins. The last chapter 5 concludes the thesis.

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# 2. LITERATURE REVIEW:

## 2.1. City Information Modelling (CIM):

City Information Modelling (CIM) is viewed in different ways yet focuses on the same objective i.e., better planning and management of cities. In 1999, (Alberti, 1999) laid down the theoretical framework for urban ecosystem modelling. According to him, an urban ecosystem model should be able to simulate the environmental stresses induced by humans under varying economic, environmental, demographic, and policy scenarios and anticipate the alterations in the impacts with regards to change in the above parameters (Alberti, 1999). His main focus was on urban metabolism and its consequences on the environment. With time, the researchers started to look at urban modelling as an integrated tool for decision-making to address other urban issues besides environmental issues especially related to the planning, design and impact of projects on the locality and communicating it to the stakeholders. The term "CIM" has been used alternatively with 3D city models and city visualization tools. (Batty *et al.*, 2000) endorsed that visualization tools aid different phases of the planning which includes swift and adequate storing and fetching ability of data, support design process and provide a visualization communication platform to disseminate the project plans and information to the relevant stakeholders (Batty *et al.*, 2000).

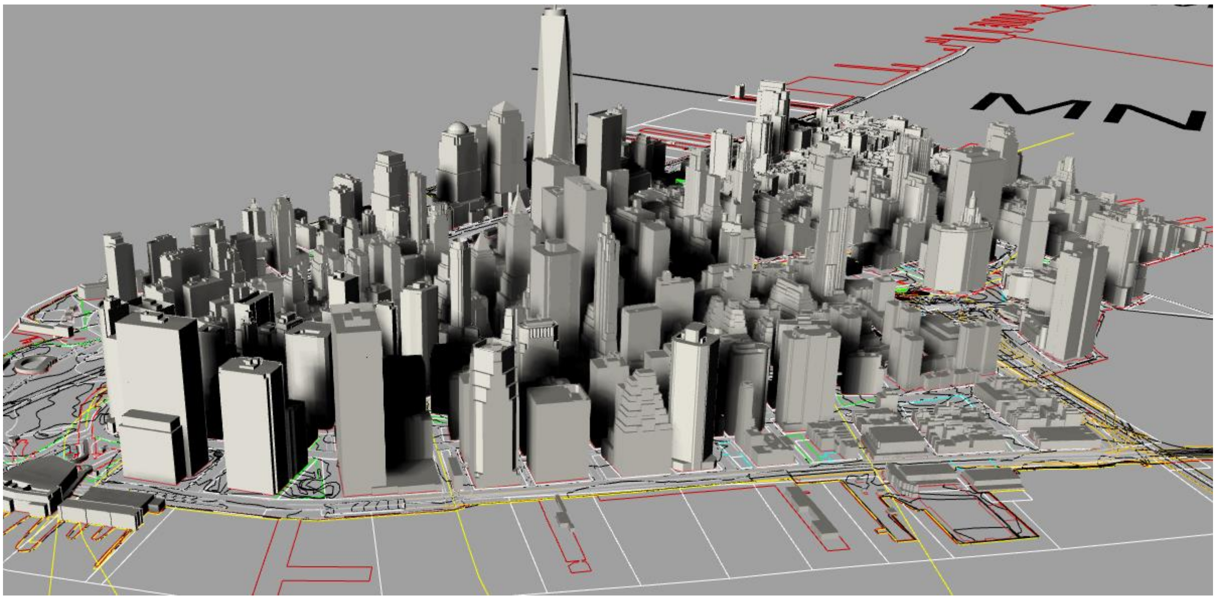


**Figure 1 –3D city model of a neighborhood in New York (Source: (*NYC 3D Model*, no date)**

(Furjani *et al.*, 2020) deduced that CIM is actually the city-level implementation of building information modelling (BIM) and 3D city models (3DCM) is integral to validate CIM. A 3D city model is ideally supposed to hold diversified data and information necessary for digital representation and to fulfil the concept of CIM (Furjani *et al.*, 2020). CIM has been garnering attention for a comprehensive approach towards urban design processes to tackle sustainability challenges (Gil, Almeida and Duarte, 2011). CIM can be considered as a digital platform where city designers can tweak the features, elements, and characteristics of design, analyse scenarios and run simulations to find optimal design solutions

(Stojanovski, 2018). GIS is widely employed for 3D city modelling and there are many methods to acquire GIS information such as 2 and 2.5D terrain maps, laser scanning, and photogrammetry (Xu *et al.*, 2014) (Žiūriene, Mešliūte and Makuteniene, 2006) (Lancelle and Fellner, 2004).

There are 4 items involved in creating a 3D city information model; (1) Data source, (2) Software or platform, (3) Modelling approach (4) Visualization tools (Žiūriene, Mešliūte and Makuteniene, 2006).

## 2.2. Building Information Modelling and City Information Modelling:

The inception of Computer-Aided Design (CAD) in the 1970s transformed the process of making drawings and with the arrival of Building Information Modelling (BIM) in the 1990s, the whole design process employing CAD was digitalized and reshaped. BIM started producing traditional drawing elements such as site plans, floor plans, elevations, sections in 2D and axonometric views, and perspectives in 3D (Stojanovski, 2018). Now BIM has become more advanced and it can perform a myriad of tasks from designing to collaboration, from budgeting to scheduling, from tracking progress to operation, maintenance to optimization, and many more (Afzal, Maqsood and Yousaf, 2017a) (Afzal, 2019). BIM can be defined as a process that involves the creation and management of virtual representation of physical and functional features of a building (Xu *et al.*, 2014). BIM is mostly used on a smaller scale contrary to CIM. 3D city models enriched with semantic information are drivers for efficient decision-making. However, very few methods exist to enrich city models with semantic information through BIM to attach the semantic information to the building elements and other infrastructural objects in 3D city models (Xu *et al.*, 2014). The individual BIM projects in a city can be unified in one platform to provide an information-rich 3D city model which is capable of integrating all the information obtained from BIM at a larger scale to take evidence-based decisions. The connection between BIM and CIM can enable real-time tracking of any changes, additions, modifications in a building from individual building level to urban level. There are 5 different Level of Detail (LoD) in a 3D city model; LoD 0 represents the terrain or footprint, LoD 1 corresponds to block models with no roof structure, LoD 2 contains roof structures, LoD 3 constitutes detailed architectural features and LoD 4 represents the walkable interiors of the model (Biljecki, 2017). The outdoor spatial information can be gathered through laser scanning and photogrammetry to the desired level of detail. However, attaining LoD 4 is not possible without BIM (Xu *et al.*, 2014). Therefore, integrating BIM with CIM is crucial for an efficient 3D city model. Notwithstanding its importance, there is no straightforward way to integrate BIM into CIM so far because of interoperability, standards, regulations, data and information quantities, and exchange incompatibility, and several pieces of research have indicated that software compatibility is one of the major issues in integrating BIM with CIM (Schaufler and Schwimmer, 2020).

## 2.3. IFC and CityGML:

The Industry Foundation Classes (IFC) is an international openBIM standard for data exchange developed by buildingSMART which represents BIM data that is exchanged and shared among different users in building construction or facility management projects (*Introduction*, no date b). While CityGML is an open standard model and exchange format to store and exchange virtual 3D models of cities and landscapes developed by the Open Geospatial Consortium (OGC) and the ISO TC211 (*CityGML | OGC*, no date). In simplified terms, IFC is used for sharing BIM data while CityGML is for CIM data.

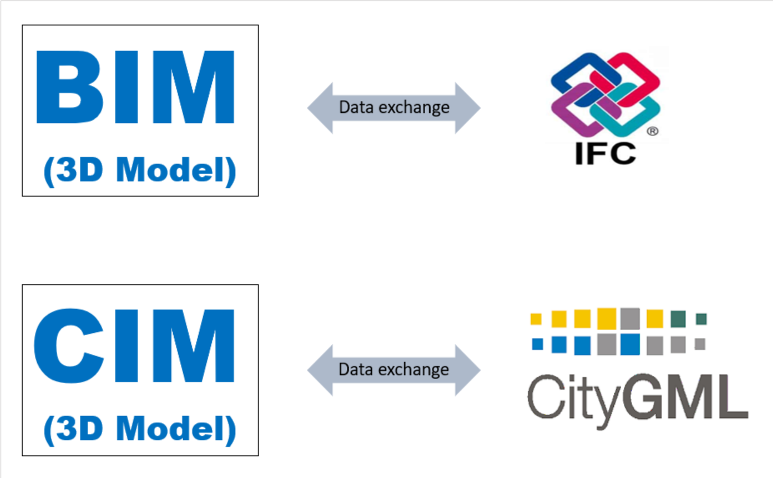


**Figure 2 – Data exchange formats for BIM and CIM**

IFC is used for a slew of purposes such as exchanging information, automating processes (Liu *et al.*, 2020b), optimization (Liu *et al.*, 2020a), running simulations. Traditional 3D modelling of infrastructures involves simplified 3D virtual representation and it does not incorporate enough information and metadata corresponding to modelled elements. Infrastructures are continuously changing during their lifetime especially design stage and cities in general, it entails a substantial flow of information which cannot be ignored. Furthermore, performing various analysis require an exchange of models (information) among different software and tools and it causes data and features losses (Tolmer *et al.*, 2013). Therefore, open standards are developed with exchange formats to create interoperability among different tools. CityGML contains less detail as compared to IFC but it includes large spatial zones (Arroyo Ohori *et al.*, 2018). CityGML contains elements of a 3D city model (El-Mekawy, Östman and Shahzad, 2011) made up of surfaces (Tolmer *et al.*, 2013) whilst IFC represents a very detailed model containing elements that are tangible such as beams, columns, walls, doors, etc., as well as non-tangible aspects such as space, activities, processes, management, etc. (Tolmer *et al.*, 2013). The integration of CityGML and IFC is highly desired as it can unlock a series of benefits at the planning and operational stages of urban areas (El-Mekawy, Östman and Shahzad, 2011).

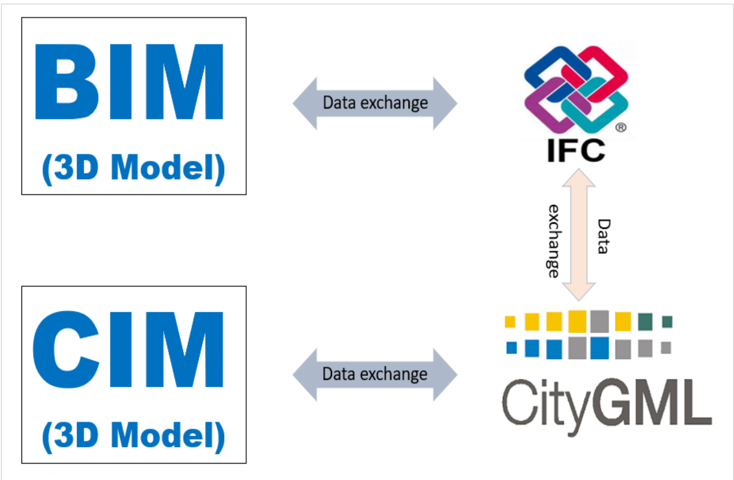


**Figure 3 – Interoperability between IFC and CityGML**

El-Mekawy et al. developed Unified Building Model (UBM) based method to convert the IFC model into a CityGML model and vice versa, however, there are still limitations in information exchange between these two different schemas (El-Mekawy, Östman and Shahzad, 2011). CityGML allows the users to define certain extensions known as Application Domain Extension (ADE) for specific applications such as noise pollution estimation, or to enhance CityGML by incorporating metadata according to the national regulations or to create interoperability among various data models (*Basic Information - CityGML Wiki*, no date). Biljecki et al. has developed an ADE for the conversion of IFC into CityGML (Biljecki *et al.*, 2021). The concept of CityGML ADEs can be extended to sustainability by developing a chained ADE data model comprised of interlinked ADEs containing all parameters of sustainability rating systems such as LEED and BREEAM.

### 2.4. CIM and sustainable urban development:

Cities are struggling to address ever-changing scenarios and issues originating from sprawling cities. The construction of buildings, infrastructure, and city practices impact the overall ecosystem as well the society and economics (Afzal, Maqsood and Yousaf, 2017b). Conventional management practices are going to be obsolete and evidence-based decision-making is going to adopt a key role in city development (Bayo, 2016). CIM can foster evidence-based and informed decision-making (Lafioune and St-Jacques, 2020). A 3D city model contains a lot of schematic data and can assist in various functions such as noise pollution mapping, urban planning, etc., (Lancelle and Fellner, 2004), however, orienting the functionality of a 3D city model with sustainable development demand deep understanding and awareness of sustainability parameters or indicators. These urban sustainability indicators can be ascertained from various platforms such as the United Nations' SDG11, LEED for Cities and Communities, or BREEAM Communities. The main intent of developing these goals or rating systems is to lay down a benchmark for the comparison of actual city performance and performance deemed optimal according to the sustainability indicators. Whilst reviewing the UN's SDG 11 and LEED for cities and communities, it becomes explicit that both systems overlap and underpin each other and the same is the case with BREEAM Communities which is obvious since LEED and BREEAM support the UN's SDG 11. "Promoting sustainable human settlements development", is the subject of Chapter 7 of Agenda 21, which emphasizes the following 8 points ("Sustainable cities and human settlements.:. Sustainable Development Knowledge Platform," n.d.):

- furnish sufficient housing for all
- better management of human settlements
- encourage sustainable land-use planning and management
- foster the consolidated provision of environmental infrastructure including water and sanitation system and drainage and solid waste management
- provide sustainable energy and transportation means in urban areas
- develop planning and management of vulnerable areas to disasters in settlements
- promote sustainable construction work

- focus on human resource development and capacity-building in urban settlements

LEED for Cities and Communities classifies sustainable urban development goals into 7 different classifications; integrative process, natural systems and ecology, transportation and land use, water efficiency, energy and greenhouse gas emission, materials and resources, and quality of life. A major portion of the sustainable development goals presented in SDG 11 is also addressed in LEED for cities and communities as elucidated in the following picture:

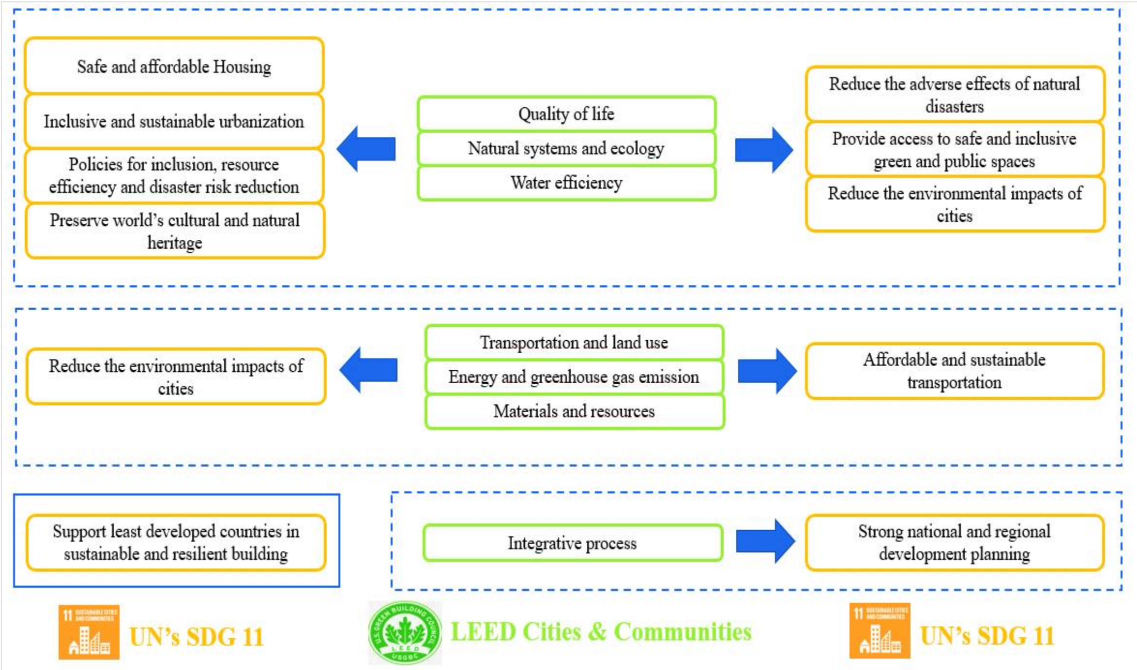


**Figure 4 – The common grounds in UN's SDG11 and LEED for Cities & Communities**

It demonstrates that sustainable urban development systems and ratings do not differ in their final goals but only in the categorization of their objectives. In this study, LEED for cities and communities is largely focused due to its quantification of sustainable urban development requirements into credit points and a scoring system to award sustainability status after the end of the evaluation. In simplified terms, LEED allows to assess the extent of sustainability in a given city.

Due to the above reasons, LEED for cities and communities is utilized in this study to accentuate the applications of CIM in regards to sustainable urban development which has not been attempted in prior studies.

## 2.5. CIM applications:

A literature review has been conducted to determine the common use cases of 3D city models which have been presented in various research papers. Since CityGML standard provides a function of ADEs to create customized applications for 3D city models, however, some ADEs are developed to perform a task which is not repeated later on or for a research paper solely so it did not extend its use (Biljecki, Kumar and Nagel, 2018). Here some of the use cases categories of 3D city models are presented which are commonly found across various research papers.

**Table 1 – Most common applications of 3D city models**

| Use Case | Description | Literature |
|---|---|---|
| **Emergency Services** | Safety (CCTVs placement), security, fire access, ambulance reach, and rescue services accessibility, etc., are all dependent on the entangled geometry of the urban infrastructure and the idea of accessing different areas and locations quickly which can be facilitated by 3D city models | (Lancelle and Fellner, 2004)<br>(Žiūriene, Mešliūte and Makuteniene, 2006)<br>(Zhu *et al.*, 2009)<br>(Xu *et al.*, 2014)<br>(Biljecki *et al.*, 2015)<br>(Dantas, Sousa and Melo, 2019) |
| **Urban Planning** | land-use planning, site location assessment, the impact of a development, community planning, and stakeholder engagement can be underpinned by a 3D digital representation of the city models | (Alberti, 1999)<br>(Lancelle and Fellner, 2004)<br>(Zhu *et al.*, 2009)<br>(Ross, 2010)<br>(Janečka, 2019)<br>(Schrotter and Hürzeler, 2020) |
| **Telecommunication Services** | Determination of suitable sites for the provision of telecommunication towers and their coverage can easily be conducted using 3D city models | (Lancelle and Fellner, 2004)<br>(Žiūriene, Mešliūte and Makuteniene, 2006)<br>(Biljecki *et al.*, 2015)<br>(Kutzner and Kolbe, 2016)<br>(Dantas, Sousa and Melo, 2019) |
| **City Services** | Water, sewage, and electricity, road network, railways, biking pathways, etc., | (Lancelle and Fellner, 2004) |

| Use Case | Description | Literature |
|---|---|---|
| | can be optimized with up-to-date 3D city models | (Žiūriene, Mešliūte and Makuteniene, 2006)<br><br>(Stojanovski, 2013)<br><br>(Melo *et al.*, 2020)<br><br>(Schrotter and Hürzeler, 2020) |
| **Marketing and Economic Development** | 3D city models support visualization of the city to determine the locations of connected uses, areas of high mobility, availability of optimal space for development, and placement of billboards | (Batty *et al.*, 2000)<br><br>(Žiūriene, Mešliūte and Makuteniene, 2006)<br><br>(Biljecki *et al.*, 2015)<br><br>(Biljecki, 2017) |
| **Real Estate Planning and Management** | 3D city models can facilitate exploiting detailed data to assess floor area, land availability, placement of building, outlook, land value, costs of development, and taxation and distance to commodities to evaluate property rates. It also enables real estate owners to manage their assets simultaneously on one platform | (Batty *et al.*, 2000)<br><br>(Žiūriene, Mešliūte and Makuteniene, 2006)<br><br>(Gröger *et al.*, 2012)<br><br>(Biljecki *et al.*, 2015)<br><br>(Biljecki, 2017)<br><br>(Janečka, 2019) |
| **Entertainment and (Virtual) Tourism** | 3D city digital representation of touristic areas and entertainment places to provide avenues for tourists and relevant people to get an idea of the geography of the city and for gaming purposes | (Lancelle and Fellner, 2004)<br><br>(Schilling, Coors and Laakso, 2005)<br><br>(Žiūriene, Mešliūte and Makuteniene, 2006)<br><br>(Biljecki *et al.*, 2015)<br><br>(Biljecki, 2017) |

| Use Case | Description | Literature |
| --- | --- | --- |
| **Environmental Quality** | Visualization of the impact of development on surrounding areas such as local pollutants linked with traffic, water pollution, noise pollution, the glare of windows causing discomfort for pedestrians or other households, location of green areas, etc. | (Lancelle and Fellner, 2004)<br>(Žiūriene, Mešliūte and Makuteniene, 2006)<br>(Ross, 2010)<br>(Biljecki *et al.*, 2015)<br>(Lafioune and St-Jacques, 2020) |
| **Web-based City Information Portals** | CIM databases can act as web-based city information platforms which are enriched with a vast amount of data such as spatial data, demographics, generic data, and any other special public features' information | (Lancelle and Fellner, 2004)<br>(Žiūriene, Mešliūte and Makuteniene, 2006)<br>(Ross, 2010)<br>(Schrotter and Hürzeler, 2020)<br>(Furjani *et al.*, 2020) |
| **Analysis and Simulations** | 3D city models enable users to conduct certain analyses and run simulations such as energy consumption, solar power generation potential, shadow studies, daylighting, urban heat island impact, etc., | (Biljecki *et al.*, 2015)<br>(Soon and Khoo, 2017)<br>(Arroyo Ohori *et al.*, 2018)<br>(Biljecki, Kumar and Nagel, 2018)<br>(Schrotter and Hürzeler, 2020)<br>(Johari *et al.*, 2020) |

There are several other isolated use cases as well which are described in the literature, however, the most common applications of 3D city models currently used by municipalities such as Zurich, Berlin, New York, Singapore, etc. are illustrated in Table 1 (Schrotter and Hürzeler, 2020) (*City Models of*

*Berlin / State of Berlin*, no date) (*3D City Model of New York City - Chair of Geoinformatics*, no date) (Soon and Khoo, 2017).

## 2.6. Static and dynamic 3D city models:

In the previous Table 1, the applications of 3D city models are mostly based on static 3D models. Currently, City information models statically represent the existing physical properties and geometries of the buildings and infrastructure (Schaufler and Schwimmer, 2020). It means that once a 3D city model has been created and put in place to perform different assessments involving visual studies and running simulations based on the existing data, it cannot adapt to tomorrow's scenarios easily. A static 3D model exhibits static outputs at a certain period in time and does not alter itself with time. Whereas cities are the complex integration of socio-economic processes, human activities, urban fabric, environment, infrastructure, systems, resources and it is ever-changing either at a slow pace or a fast pace. In order to respond to any real-life change in the city characteristics, the static 3D city model has to be updated with new information. This process is manual and not very aligned with the spirit of "Smart City". A smart city seeks to create a symbiosis among all the elements of a city including humans, physical structures, digital systems, assets, services resources, etc., (Chaturvedi and Kolbe, 2016) with the integration of Information and Communication Technologies (ICT) and Internet of Things (IoT) (*Smart cities | European Commission*, no date). Smart cities have been developing data-sharing platforms to integrate physical infrastructure with digital infrastructure through sensors, meters, etc., for real-time data exchange (Ruohomaki *et al.*, 2018). This timely data flow enables city governments to allow machine-to-machine automated or semi-automatic decisions. In order to catch up with the progress of smart cities, static 3D city models have to manifest bilateral data flow which is not possible without extending a connection of the model to the real world which can give spatial reference to the information (Chaturvedi and Kolbe, 2016). Chaturvedi and Kolbe have created an Application Domain Extension (ADE) for the CityGML to enable the integration of sensors with the 3D city model for dynamic data exchange (Chaturvedi and Kolbe, 2016). A dynamic 3D model represents properties that change with time. For instance, energy consumption, $CO_2$ generation, occupancy, etc., and dynamic models can play a major role in a city for sustainable urban development due to their responsiveness (Schaufler and Schwimmer, 2020).

Since CIM represents static data which is mostly comprised of physical properties such as dimensions, alignment, geography, and geometry, therefore, it is difficult to establish a relation between a static state and a time-dependent scenario that can fulfil the UN SDGs. Still, CIM can perform various analyses on static models such as urban heat island, wind flow, mobility, energy, solar potential, shading, etc., which can help in assessing sustainability goals but to a limited extent (Schaufler and Schwimmer, 2020) and dynamic models can perform an extended level of sustainability studies. Therefore, dynamic models are emphasized to create the digital mirror images of the physical objects i.e., digital twins.

## 2.7. Digital twin (DT):

Digital Twin is an emerging technology (Sepasgozar, 2021). The use of the word "technology" is intentional here since Sepasgozar rendered DT as a technology by comparing it with other technologies and it is deemed the same by the author of this thesis. A digital twin is a digital copy of a physical object/s and in an urban context, it is a digital mirror image of a city or a neighbourhood (Ruohomaki *et al.*, 2018). A digital twin acts as a bridge between virtual models and real-life objects to address challenges human society is struggling with (*ARUP Digital twin: towards a meaningful framework*, 2019). The capabilities of digital twins are much more than solely visual depiction which includes digital modelling tools and infrastructure. A digital twin enables real-time data to flow between built and virtual environments allowing remote monitoring, controlling, inspecting, and automatic or semi-automatic decision making (Sepasgozar, 2021). The importance of digital twins is evident from its rising demand which is expected to reach USD 106.26 Billion in 2028 from USD 3.19 Billion in 2020 as per Emergen Research and demand for digital twin of smart cities is contributing majorly in this spur (*Digital Twin Market by Type, Technology, Application and Region | Industry Size USD 106.26 Billion in 2028*, no date).

City administrations are mired down by new challenges posing obstacles in the planning and management of cities. Cutting carbon emissions is one of the major tasks which cities need to undertake in their bid to fight global warming and manage urban metabolism effectively for sustainable urban development. Digital twins and smart cities offer some possibilities to make effective decisions that are vital for sustainable urban development (*ARUP Digital twin: towards a meaningful framework*, 2019).

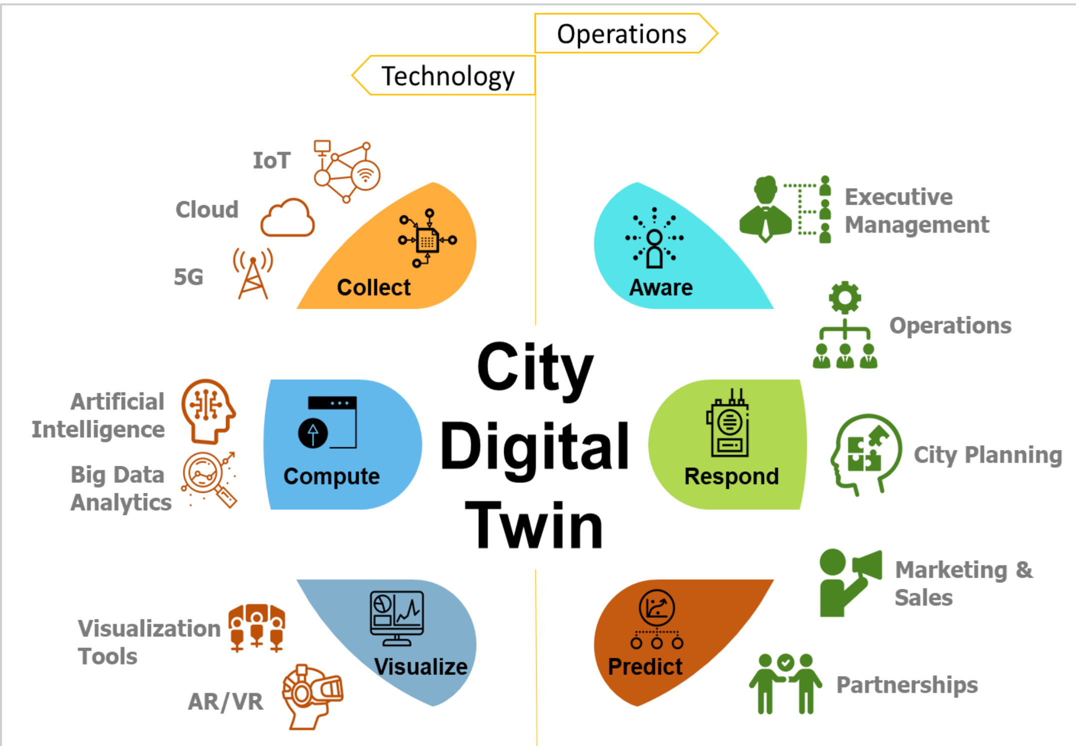


**Figure 5 – City Digital Twin tools and operational amplification (Source:** "Huawei Enterprise," n.d. and "IDC - Research - New Research," n.d.)

The above figure illustrates the technology which is pivotal for the digital twin of a city and its outcomes on the operational side.

Cities leading digital twin implementation and applying cutting-edge technologies are sharing their outcomes and data through open data platforms such as Zurich and Singapore (Schrotter and Hürzeler,

2020) (*Virtual Singapore*, no date a) to enable other city administrations to put collective effort towards a sustainable and resilient future.

The digital twin of Singapore is known as Virtual Singapore which is setting precedent for other cities. A dynamic 3D city model and web-based interactive open data portal contain spatial features such as buildings, water bodies, and transportation infrastructure, landscapes and city furniture, etc. The model is enriched with dynamic data in real-time including climate, mobility, etc., and this data is utilized in different ways such as running emergency simulations, climate change assessment, analysing mobility to plan infrastructure development (Crawford, no date).

Similarly, the City of Zurich has been developing a digital twin with the ultimate intent to simulate temporal scenarios such as urban planning linked with climate change. The digital twin for the City of Zurich focuses on a constant addition of information into a 3D spatial data repository and lifecycle management of elements individually as well as collectively. Currently, the digital twin can be applied for spatial cooperation with internal and external participants e.g., planned urban development projects or scenarios can be integrated. It also establishes the rationale for different assessments and calculations such as visibility, noise propagation, and solar potential evaluation, shadow estimations, flood simulations, etc. Further applications are being developed such as 3D utility network cadastre, improved integration of BIM and GIS, lifecycle management, etc (Schrotter and Hürzeler, 2020) (*Digital Twin - City of Zurich*, no date).

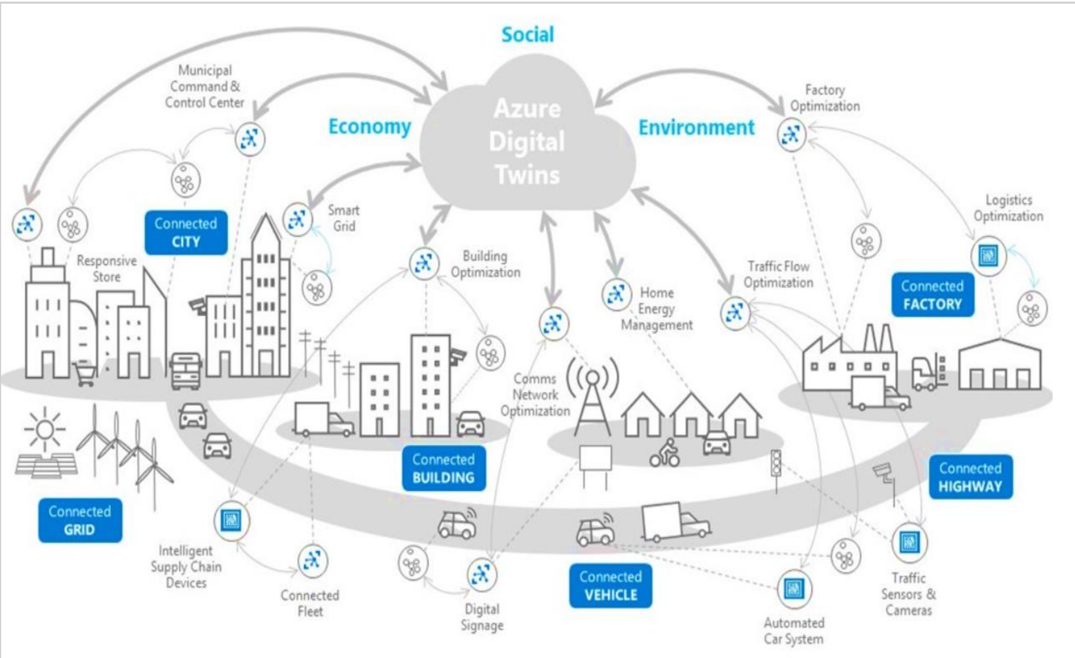


**Figure 6 – Azure's framework for integration of physical assets into a digital twin (Source:** "Announcing Azure Digital Twins," n.d.**)**

For an effective digital twin, all three dimensions of sustainability i.e., social, economic, and environment must be fostered simultaneously. Social, economic, and environmental dimensions are interlinked and integrated; augmenting any one dimension can uplift the other dimensions but to a limited extent and it may cause a decline in the other dimension. For instance, enhancing GDP may improve the liveability (social) but it can cause Greenhouse Gas emissions (GHG) due to increased industrial operations. Therefore, focusing on all the pillars of sustainable urban development is necessary for digital twins as well. The social aspects such as demographics, liveability, quality of life, justice, human rights, house affordability, etc., should be (ideally) included in a digital twin to estimate sustainable urban development holistically and it has the potential to uphold the social dimension as well.

However, with all the bright outcomes that digital twin promises come certain issues also such as data synchronization, high latency, and energy consumption, security and privacy risks, etc (Schaufler and Schwimmer, 2020). These challenges have to be addressed before unlocking its full potential.

## 2.8. Case studies:

Many city governments have realized the importance of 3D city models in fostering public services and improving the overall quality of life in the cities. 3D city models have been created and shared (mostly) on open web portals so that other cities can learn from their experiences. Different platforms have been used for the development of 3D models with varying Level of Detail (LoD). Several applications have been defined by every city for its 3D city model and some have undertaken the advanced steps to transform 3D city models into digital twins as discussed in the last section. In this section, 5 cities (New York, Singapore, Berlin, London, and Helsinki) are discussed which have implemented CIM in the planning and management of their cities.

### 2.8.1. New York:

A 3D city model has been created for New York City based on 2014's aerial survey and it includes all the buildings present in that survey. The CityGML standard by Open Geospatial Consortium (OGC) has been followed as the basis to develop massing models of building from Level of Detail (LoD) 1 and 2. The model contains roofs, facades, and ground plane with the inclusion of all major roofs in the modelling. The model does not contain domes and rounded roofs. Any roof attachments such as chimneys, antennas, solar panels, parapets, etc., are not modelled. Permanent structures smaller than 10 feet (3 meters) on a side such as small towers, elevator shafts, stairs, etc., are excluded from the model (*CityOfNewYork / nyc-geo-metadata*, no date). The majority of the model possesses LoD 1, however, almost 100 iconic buildings are modelled with LoD 2. The model is a one-time creation and updates or extensions have not been considered yet but may be considered in the future. The model and its pertinent metadata are publicly available (*NYC 3D Model Download*, no date). The model is available for the public at 3D City Database (3Dcitydb) portal which implements the CityGML schema (*3DCityDB Database – Homepage*, no date).

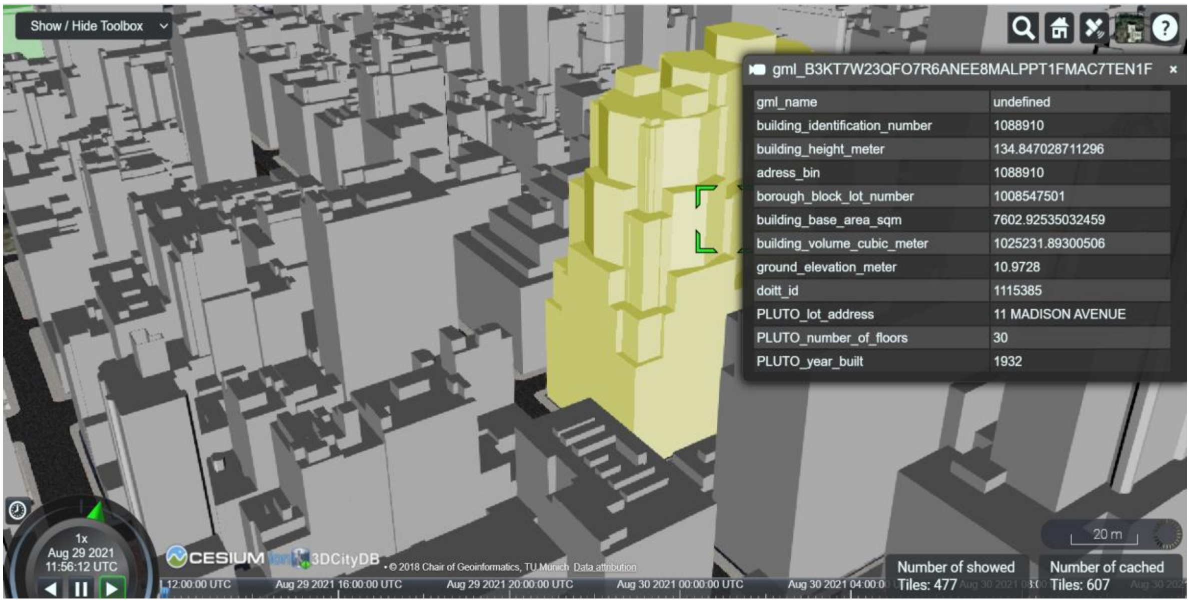


**Figure 7 – A view of 3D NYC model in 3Dcitydb portal with metadata of the selected building (Source:** "3DCityDB Database – Homepage," n.d.)

The city government of New York is applying the 3D NYC model into many applications such as wind or shadow simulations, urban design, building volume calculation (*CityOfNewYork / nyc-geo-metadata*, no date), solar irradiation assessment, traffic analysis, determination of potential repair costs of streets and land use planning and management (*3D City Model of New York City - Lehrstuhl für Geoinformatik*, no date b).

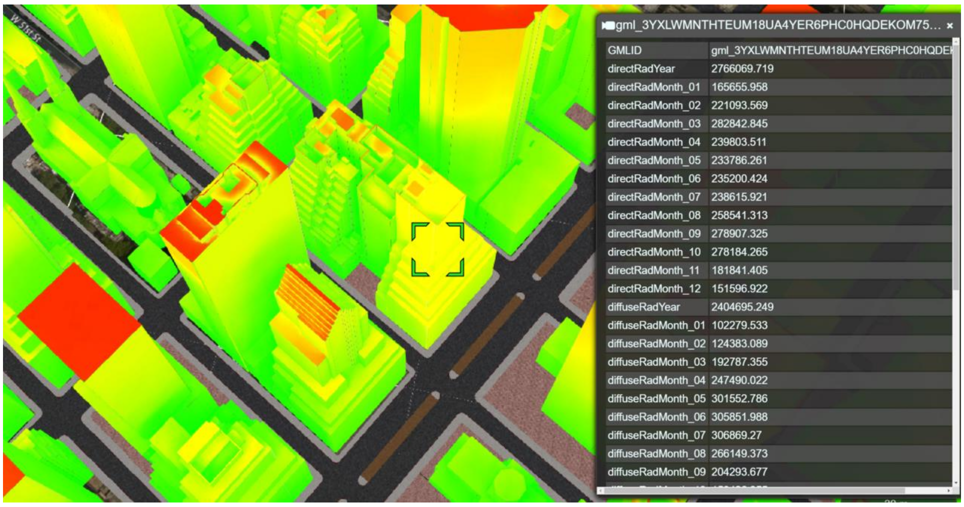


**Figure 8 – Estimation of solar irradiation for buildings in Central Manhattan in kWh/year ranging from bright green (low irradiation values) over yellow to red (high irradiation values) (Source:** "3D City Model of New York City - Lehrstuhl für Geoinformatik," n.d.)

### 2.8.2. Singapore:

The Singapore Land Authority (SLA) has launched a project called the 3D National Mapping to develop and maintain a 3D map of Singapore. The data for 3D mapping was collected in two steps; utilization of aerial lidar scanning and imaging, and street mobile lidar scanning and imaging for data collection. The CityGML standard by OGC has also been employed here to develop a 3D city model of Singapore known as Virtual Singapore. The Level of Detail (LoD) used for modelling Virtual Singapore is from 0 to 2 depending on the modelled element. The 3D city model of Singapore is comprised of terrain, buildings, transportation, city furniture, bridges, tunnels, water bodies, and vegetation. Modelling of 3D tunnels is carried out by driving a mobile data collection vehicle through the tunnel to develop the 3D profile of the tunnel. Water bodies have been modelled by fixing a constant depth of 5 meters across all water bodies in the model. Also, a generalized vegetation cover has been considered without differentiating between plant type, height, etc., and a general height from 15 to 20 meters has been considered for vegetation throughout the model. For storing and maintaining the 3D city model, the 3Dcitydb database has been used similarly to the NYC model. The methods to adopt for the update of the model with new objects have been weighed by assessing different alternatives such as the ground level laser scanning, satellite images, and Building Information Models (BIM) and the most optimal technique will be selected in the future to update the model (Soon and Khoo, 2017).

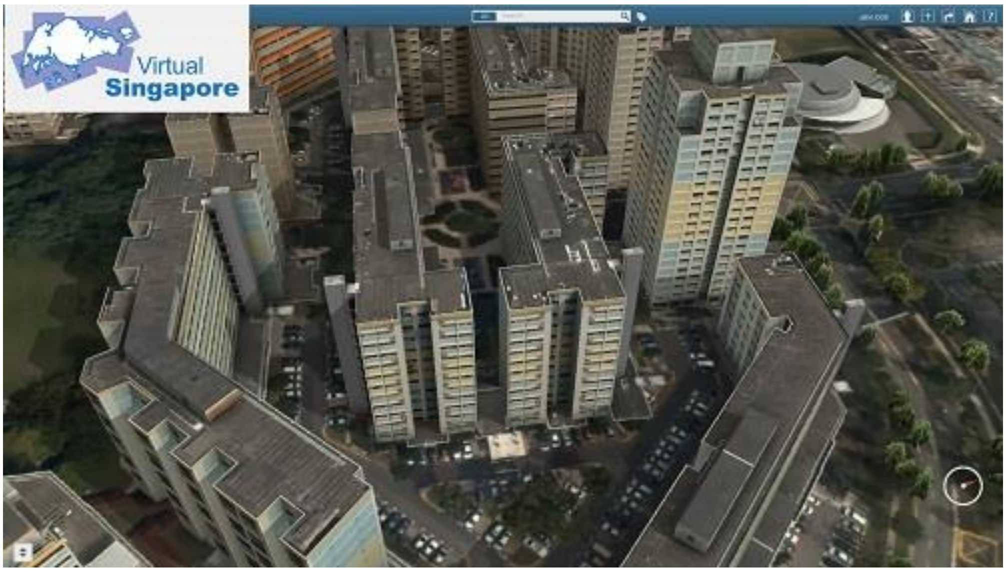


**Figure 9 – A view of the 3D city model of Singapore (Source:** "Virtual Singapore," n.d.)

There are several intended uses of Virtual Singapore to enable the government of Singapore to acquire capabilities of virtual experimentation such as visualization of 3G/4G networks' range coverage, virtual test-bedding such as 3D modelling of a new sports hub with semantic data within Virtual Singapore to model and simulate crowd spread to plan evacuation routes during an emergency, informed planning and decision-making such as rendering Virtual Singapore as a data enriched and integrated platform to create analytical applications e.g., an app for analysing transport flows or pedestrian movement behaviours, research and development by the provision of enriched data to the researchers for spurring innovation and developing new technologies. Furthermore, it has additional applications such as solar energy potential determination, virtual tours of Singapore, parking spaces calculations, etc. (*Virtual Singapore*, no date b).


**Figure 10 – Querying the number of parking spaces available and quantity of trees in the Virtual Singapore (Source:** “Virtual Singapore,” n.d.)

### 2.8.3. Berlin:

A semantic 3D city model has been created for Berlin, initially developed in 2007-2009, based on aerial photogrammetry in August 2018. The model has been created following the CityGML standard of OGC. The model contains more than 560,000 buildings that have roof details to Level of Detail (LoD) 2. However, the model does not contain metadata pertinent to buildings. The city administration of Berlin has made 3D city model of Berlin available to the public and it can be downloaded in 8 different formats under the umbrella of the Open Data Initiative of the state of Berlin (*VisualizationBerlin – 3DCityDB Database*, no date) (*Berlin 3D - Download Portal* , no date).

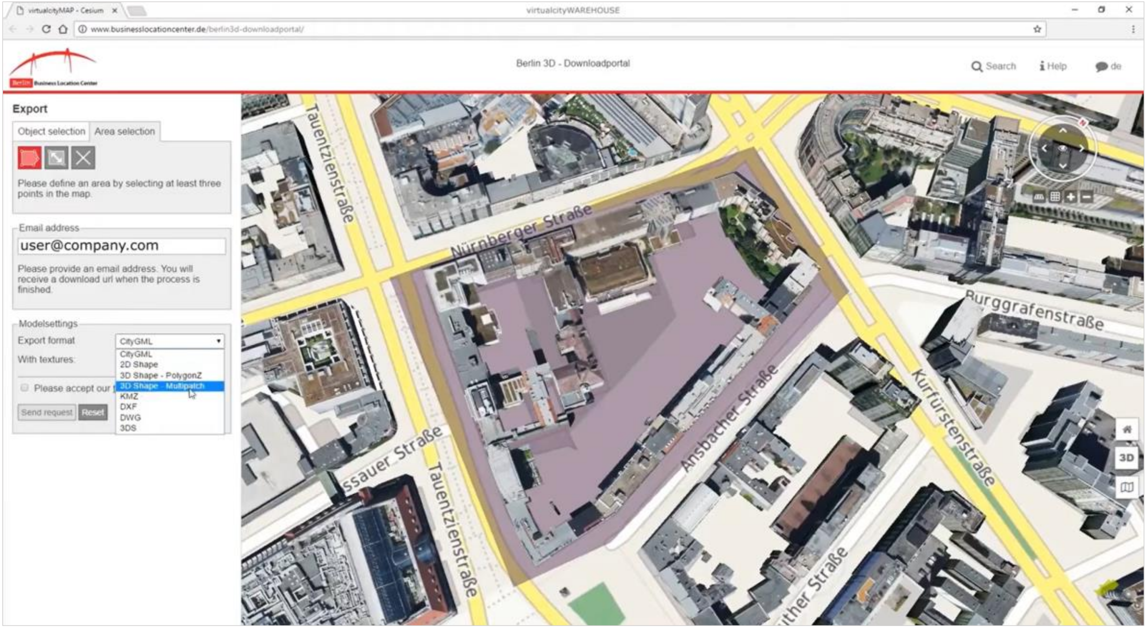


**Figure 11 – A view of the 3D city model of Berlin and the list of available formats (Source:** “Berlin 3D - Download Portal ,” n.d.)

The state of Berlin has indicated to apply this 3D city model for various urban planning and management practices based on visualizations and virtual tours (*Berlin Economic Atlas - Berlin in the third dimension*, no date).

### 2.8.4. London:

A 3D city model of Central London has been developed using stereophotogrammetry from high-definition images taken in 2016. The normal buildings are modelled with Level of Detail (LoD) 2 and some iconic buildings are present in LoD 3 as well. The 3D city model of London was developed for commercial purposes and AccuCities is involved in its development and updating. AccuCities has the ability to include the future buildings in the 3D city model by collecting information from planning portals and transform submitted drawings into 3D block models to represent the planned development in the best way. The terrain for this 3D city model is not flat but it is modelled with the help of manual photogrammetry and is accurate up to 20 cm in all axis at curb level. The model contains roads, man-made surfaces, vegetation, water bodies, bridges, embankment walls and river structures (Lafioune and St-Jacques, 2020) (*Level 3 3D Models of London | AccuCities*, no date).

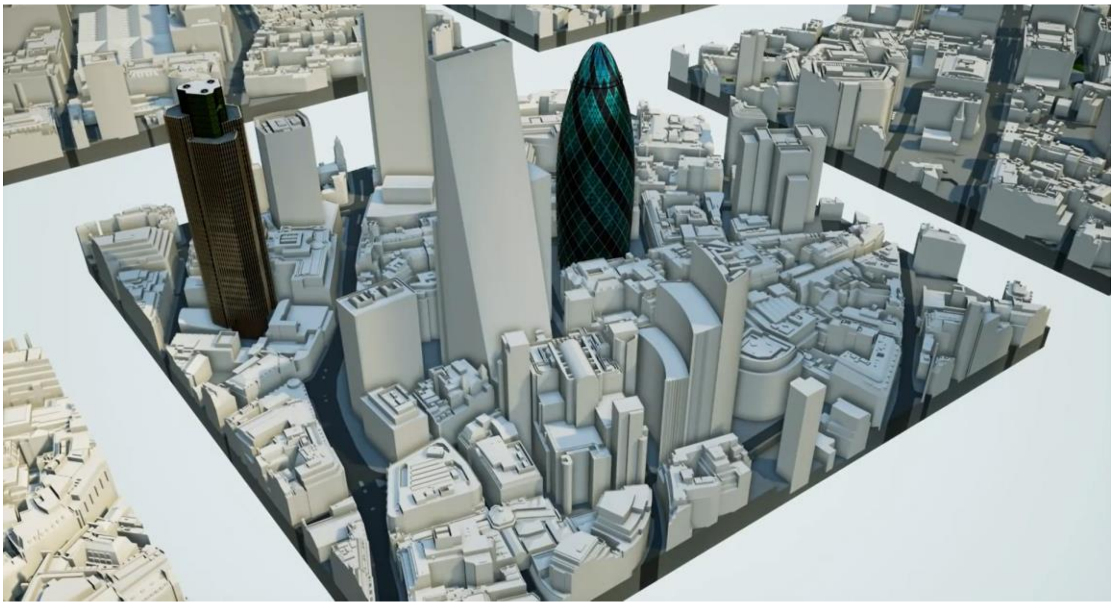

**Figure 12 – A view of the London 3D city model (Source:** “Level 3 3D Models of London | AccuCities,” n.d.)

The 3D city model of London is developed using Unreal Engine 4. Due to its commercial purposes, the 3D model is not available openly to the public but it can be purchased from AccuCities. The model is available in various formats such as AutoCAD Solid DWG, SketchUp SKP, and Filmbox FBX (*Level 3 3D Models of London | AccuCities*, no date). The 3D model can be used for assessing different urban planning practices, simulations, analysis, evaluation of development site, visualisation and analysis proposed designs, etc., by planners, developers, architects, and city administrators, etc.

### 2.8.5. Helsinki:

The 3D city model of Helsinki is developed using aerial lidar to create a reality mesh of buildings. The 3D city models of Helsinki are available in two forms: a semantic city information model and a visually high-quality reality mesh model. Buildings are modelled with two Level of Detail (LoD) 1 and 2. The buildings with LoD 2 contain architectural textures as well. OGC’s CityGML standard has been used for the model. The buildings contain some generic information related to the buildings as well. The model is also available in various formats for better interoperability. Helsinki is using its database for storing and managing the 3D city model (*City Model of the Future: Helsinki 3D*, no date; *3D models of Helsinki - Helsinki Region Infoshare*, no date).


**Figure 13 – Helsinki 3D city model (LoD2) with textured surfaces (Source**: "Helsingin 3D," n.d.)

The relevant data of the Helsinki 3D city model is openly accessible to the common public. This model can be used for various purposes such as analysis of energy consumption, solar energy potential, greenhouse gases emission or the environmental impacts of traffic, etc. It also intends to develop a citizen interaction platform where citizens can place their feedbacks to participate in city public services such as recording the requests for more parks, parking spaces, etc. (*3D models of Helsinki - Helsinki Region Infoshare*, no date). The government of Helsinki has incorporated energy-related data into the model as well as illustrated in the following picture:


**Figure 14 – Energy data stored for each building in the 3D city model of Helsinki (Source**: "Helsinki Energy and Climate Atlas," n.d.)

# 3. METHODOLOGY:

LEED for cities and communities and BREEAM Communities have presented many parameters majorly in a quantitative aspect. These parameters match with the UN SDG 11 goals also. Some prior research has been carried out in establishing a link between city information modelling and sustainable development. However, researchers are still struggling to establish a vivid scope or direction for CIM to assume an instrumental role that can analyze the extent of sustainable development in an urban area. Therefore, an effort has been made in this thesis with the intent of creating a comprehensive checklist of LEED criteria measurable by 3D city information models. In this research, only LEED criteria has been used since the purpose is to show how CIM can be applied as a catalyst for sustainable urban development. It has been investigated which tasks and processes of LEED can be fulfilled by using 3D city models. For this purpose, all the credits of LEED have been analyzed to establish which parameters can be readily investigated by CIM and some recommendations have been disseminated to enhance the scope of CIM in measuring a wide range of sustainability indicators. Furthermore, the potential of CIM has also been evaluated to weigh its possible uses and limitations through literature review to present a clear picture of what CIM can do and what it cannot (at least by now). The goal is to analyze the possible intervention of CIM in urban sustainable development assessment systems such as LEED which also coincide with the UN SDG 11. Urban sustainability assessment tools have grabbed substantial attention of researchers especially LEED for cities and communities which focuses mainly on the physical features of a city such as transportation, land use, and infrastructure, however, during literature review it appeared that very nominal research has been carried out in CIM facilitated sustainable urban development assessment delineated by LEED or BREEAM. This paper can serve as a state-of-art reference for sustainability-focused stakeholders that are investing or doing research in city information modelling and exploring its applications to investigate the degree of sustainable urban development in the cities.

A conceptual 3D model for a small neighborhood based on the construction pattern of a small area around Viale Legioni Romane, Milan has been created using Rhinoceros software representing objects such as buildings, streets, and parks with block modelling technique i.e., generating 3D building models by building footprint extrusion. The map from gmap-pedometer has been imported into Rhino representing the location of buildings, streets, and parks. After scaling the map, the objects are modelled in Rhino. A simple approach has been followed since it incorporates a huge amount of data, resources, effort and cost to create a 3D city information model. In this study, the buildings are modeled as blocks that correspond to LOD 1. The parks and vegetation are modelled to varying heights. It is to be noted that the base height of the objects is 0 m and the actual terrain has not been incorporated in this study. The main motive is to demonstrate the benefits of 3D urban models. Some simulations have also been conducted using the Urban Modelling Interface (umi) tool developed by the Sustainable Design Lab of the Massachusetts Institute of Technology (MIT). This tool is a plug-in for Rhino and it analyzes the environmental performance of urban areas and settlements in terms of operational and embodied energy use, daylighting potential, and walkability ("Urban Modeling Interface | MIT Sustainable Design Lab," n.d.).

**Figure 15 – Shadow simulation of the developed conceptual 3D city model**

Apart from 3D modelling, a state-of-the-art study has been performed in establishing a link between city information modelling and sustainable urban development.

### 3.1. LEED for cities and communities:

LEED for cities and communities is a certification program initiated by the United States Green Building Council (USGBC) focusing on sustainable urban development in cities and communities. It addresses many factors such as nature, water, energy, waste management, transportation, quality of life, etc. ("LEED for Cities and Communities | U.S. Green Building Council," n.d.).

LEED for cities and communities have divided the sustainable urban development tasks into 7 categories; Integrative Process (IP), Ecology and Natural Systems (NS), Transportation and Land Use (TR), Water Efficiency (WE), Energy and Greenhouse Gas Emission (EN), Materials and Resources (MR), and Quality of Life (QL). There are two other categories; Innovation (I) which entails the implementation of some innovation or novel methods in achieving the requirements of prior categories and Regional Priority (RP) which focuses on fulfilling credits that are considered pertinent concerning the region where the city is located. The tasks of every category have been divided into two types i.e., prerequisites (P) and credits (C). A prerequisite is a mandatory requirement that has to be fulfilled to get the LEED certification and all the prerequisites of each category have to be accomplished. On the other hand, the credits are not an obligatory requirement, however, every credit carries a certain score and the number of credits fulfilled determines the total points acquired by the city or community. The maximum possible points are 110 and 40 is the minimum score to get certified. There are 4 levels of LEED certification and each level corresponds to a certain threshold of points indicating the quality of sustainable urban development. The four levels of LEED certification are presented below (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021):

- Certified: 40 points
- Silver: 50 – 59 points

- Gold: 60 – 79 points
- Platinum: 80+ points

The aforementioned categories and credits do not weigh equally in terms of allocated points which in turn indicates the worth of every category and task. It can also be propounded that the points are assigned to the credits based on their impact and overall effort required for their compliance. The following table shows the points every category offers:

**Table 2 – Possible points for every category of LEED for cities and communities**

| **Category** | **Possible Points** |
|---|---|
| **INTEGRATIVE PROCESS** | 5 |
| **NATURAL SYSTEMS AND ECOLOGY** | 9 |
| **TRANSPORTATION AND LAND USE** | 15 |
| **WATER EFFICIENCY** | 11 |
| **ENERGY AND GREENHOUSE GAS EMISSIONS** | 30 |
| **MATERIALS AND RESOURCES** | 10 |
| **QUALITY OF LIFE** | 20 |
| **INNOVATION** | 6 |
| **REGIONAL PRIORITY** | 4 |
| **TOTAL** | **110** |

The percentage weightage of every category is illustrated in the following figure.

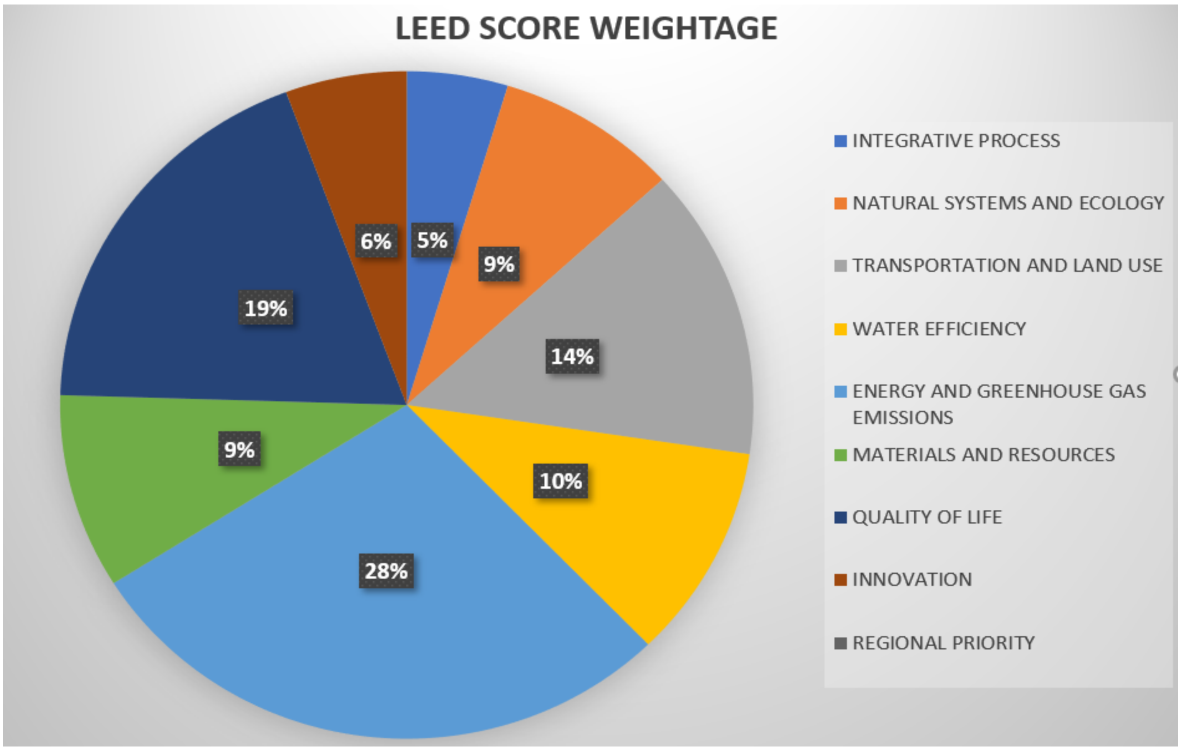


**Figure 16 – Percentage weightage of LEED for cities and communities categories**

In the LEED for cities and communities guide, there are two different scoring systems for cities and communities (some credits have different points for cities and communities), the point system for cities has been used in this study. Also, Innovation (I) and Regional Priority (RP) specifications and points are not considered in this study since these points vary on a project-to-project basis since every project may have different exemplary performance, innovative approaches, and regions. Therefore, these two categories are not analyzed in relation to CIM.

A connection between LEED for cities and communities and the United Nation's sustainable development goal (SDG) 11 has also been made in the previous chapter to validate that city information modelling is a valuable tool for sustainable development of a city or community. Previous researches indicate diverse uses of 3D city information models and seem to agree that the complete potential of 3D urban models is yet to be explored (Biljecki *et al.*, 2015). Also, there is not ample research on linking city information modelling with the evaluation of sustainability parameters. Therefore, a thorough review of LEED requirements for cities and communities in terms of 3D city models has been made to develop a sustainability-oriented framework for utilizing 3D city models. Many parameters have been identified which can be evaluated and fulfilled by using city information models and relevant roadmaps are formulated.

**Table 3 – CIM based analysis of LEED parameters**

| LEED CREDIT | DESCRIPTION | CIM APPLICABILITY |
|---|---|---|
| **INTEGRATIVE PROCESS (IP)** | | |
| **IP Credit: Integrative Planning and Leadership** | Develop a synergetic plan that focuses on the vision, mission, major goals, and objectives of the city | No |
| **IP Credit: Green Building Policy and Incentives** | Introduce policies, rewards, and programs to facilitate design, construction, and operation of green buildings or disclose energy performance data | Yes |
| **NATURAL SYSTEMS AND ECOLOGY (NS)** | | |
| **NS Prerequisite: Ecosystem Assessment** | Prepare an ecosystem assessment of Topography, Soils, Vegetation and Habitat, and Hydrology and Aquatic Ecosystems and describe their influence on city planning and development. | Partially |
| **NS Credit: Green Spaces** | Provide green areas within accessible distance for the overall well-being of the citizens and better environment of the city | Yes |
| **NS Credit: Natural Resources Conservation and Restoration** | Preserve and rehabilitate the natural resources within the city | *Yes* |
| **NS Credit: Light Pollution Reduction** | Minimize light pollution to balance the natural light patterns to reduce negative impacts on public health, ecosystem, sky visibility, and wildlife | Yes |
| **NS Credit: Resilience Planning** | Prepare vulnerability and capacity assessment of the city for climate change, natural and man-made hazards, and extreme events, and prepare a resilience plan for the city to tackle the above risks | No |
| **TRANSPORTATION AND LAND USE (TR)** | | |

| | | |
|---|---|---|
| **TR Prerequisite: Transportation Performance** | Facilitate non-vehicular transportation by encouraging public transport, bicycling, and walking to reduce Vehicle Miles Travelled (VMT) per capita and pollution | Yes |
| **TR Credit: Compact, Mixed Use and Transit Oriented Development** | Promote development in compact, human-scaled, walkable, and universally accessible centers and neighborhoods that connect to public transit and offer diverse uses and services | Yes |
| **TR Credit: Access to Quality Transit** | Encourage the population to take diverse transportation means other than their motorized vehicles by deploying safe and comfortable transit stops and frequent transits | Yes |
| **TR Credit: Alternative Fuel Vehicles** | Facilitate alternative fuel consuming transportation to reduce the usage of conventional fossil fuel vehicles by providing charging points and alternative fuel stations | Yes |
| **TR Credit: Smart Mobility and Transportation Policy** | Implement smart technologies and strategies to provide smart, efficient, and adequate transportation to the citizens | Yes |
| **TR Credit: High-Priority Site** | Conserve historic structures and sites and encourage growth and redevelopment on brownfields, infill sites, and other priority locations | Yes |
| **WATER EFFICIENCY (WE)** | | |
| **WE Prerequisite: Water Access and Quality** | Provide equitable access to clean drinking water, sanitation services to all the population and prevent pollution from sewage and stormwater discharge | Yes |
| **WE Prerequisite: Water Performance** | Encourage water management by reducing water demand and consumption per capita in the city | Yes |
| **WE Credit: Integrated Water Management** | Decrease freshwater consumption by an integrated water management process to exhibit that the ratio of water withdrawals for human use to the total freshwater available is below 0.2 | No |

| | | |
|---|---|---|
| **WE Credit: Stormwater Management** | Implement stormwater management strategies to avoid flood risks and associated damages and recharge groundwater | Yes |
| **WE Credit: Smart Water Systems** | Implement smart technologies to enhance the operational efficiency of water management systems | Yes |
| **ENERGY AND GREENHOUSE GAS EMISSIONS (EN)** | | |
| **EN Prerequisite: Power Access, Reliability and Resiliency** | Provide power supply to all sectors of the population, implement non-stop monitoring protocols and ensure backup power availability for essential, critical, and emergency services in case of a disaster or power outages | Partially |
| **EN Prerequisite: Energy and Greenhouse Gas Emissions Performance** | Prepare an emissions inventory to promote energy management and grow towards a zero-energy and emissions city | Yes |
| **EN Credit: Energy Efficiency** | Improve energy efficiency by installing energy-efficient fixtures and devices in the city | No |
| **EN Credit: Renewable Energy** | Promote renewable energy supply to reduce negative impacts linked with fossil fuel energy | Yes |
| **EN Credit: Low Carbon Economy** | Encourage low carbon economy by disintegrating economic growth from greenhouse gas emissions | No |
| **EN Credit: Grid Harmonization** | Promote user participation in energy use optimization to augment operational efficiency of the energy system | No |
| **MATERIALS AND RESOURCES (MR)** | | |
| **MR Prerequisite: Solid Waste Management** | Provide 100% coverage to all city population or buildings by waste management facilities and prepare a solid waste management plan to handle waste efficiently | No |

| | | |
|---|---|---|
| **MR Prerequisite: Waste Performance** | Promote waste management by diverting maximum waste from landfills | Yes |
| **MR Credit: Special Waste Streams Management** | Adopt strategies to handle special waste streams by diverting them from landfills and incinerators and recovering and recycling reusable materials. | Yes |
| **MR Credit: Responsible Sourcing for Infrastructure** | Promote materials and products for which life cycle assessment has been performed and their extraction is performed responsibly | No |
| **MR Credit: Material Recovery** | Develop mechanisms to recover materials from waste streams and collection and return of these materials back to the manufacturer | No |
| **MR Credit: Smart Waste Management Systems** | Implement smart solutions or strategies for waste management to handle at least 20% of the waste generated | Yes |
| **QUALITY OF LIFE (QL)** | | |
| **QL Prerequisite: Demographic Assessment** | Prepare a comprehensive narrative of population demographics and housing features of the city | Yes |
| **QL Prerequisite: Quality of Life Performance** | Track and evaluate parameters related to the living standards of all population | Yes |
| **QL Credit: Trend Improvements** | Exhibit improvements in parameters related to the living standards of all population | Yes |
| **QL Credit: Distributional Equity** | Promote equitable economic progress and promote access to community services to all | Yes |
| **QL Credit: Environmental Justice** | Tackle conditions that may be conducive to neighborhoods or populations being influenced by environmental pollutants. | No |
| **QL Credit: Housing and Transportation Affordability** | Furnish a suitable and diverse supply of location-efficient and affordable housing options for all the residents | No |

| | | |
|---|---|---|
| **QL Credit: Civic and Community Engagement** | Encourage an inclusive and socially integrated community and support their participation in local decision-making. | No |
| **QL Credit: Civil and Human Rights** | Adopt a mechanism that ensures the civil and human rights of all people are fundamental | No |

### 3.1.1. IP Credit: Integrative planning and leadership:

It involves creating a multidisciplinary symbiosis of city or community systems and support feasible and optimal outcomes. A wide range of stakeholders provides their input to foster economic, social, and environmental welfare (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). A 3D city model can definitely elicit increased awareness and ease the process of determining vision, mission and key goals, however, this process is more based on describing major targets and developing a strategy to achieve them.

### 3.1.2. IP Credit: Green building policy and incentives:

There are 3 pathways to earn this credit. This credit requires to introduce policies, rewards, and programs to facilitate design, construction, and operation of green buildings or disclose the energy performance of public or private buildings using a recognized tool such as ENERGY STAR Portfolio Manager, Arc Skoru, or any local tool (*LEED v4.1 CITIES AND COMMUNITIES EXISTING,* 2021). Option 3 of this credit requires the disclosure of energy performance data of the buildings. Storage of energy data and its comparison with benchmarks is possible through smart metering infrastructure (Francisco, Mohammadi and Taylor, 2020). It is also highly desirable for a 3D city model to be able to document energy data of buildings for evaluating the collective performance of buildings at an urban scale. Therefore, a dynamic 3D city model capable of recording energy performance data can allow its disclosure with the integration of smart metering infrastructure and this data is usually publicly available so it can be used to fulfil the requirements of option 3.

### 3.1.3. NS Prerequisite: Ecosystem assessment:

This prerequisite entails an assessment of existing ecosystem situations and services rendered by ecosystems, built landscapes, and other open spaces to guide the urban development besides conservation and restoration actions. The eco assessment is to be prepared for the following areas: topography, soils, vegetation and habitat, and hydrology and aquatic ecosystems to demonstrate their influence on city planning and development (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). A city information model can partially be used for ecosystem assessment especially for locating landscapes, open spaces, aquatic bodies (Soon and Khoo, 2017), flood risk areas (Schrotter and Hürzeler, 2020) and their influence on city development and it can demonstrate soil and plants location (Ortege-Córdova, 2018) and level of pollution but current technology limits its ability to conduct a holistic assessment to determine various factors such as soil condition, pollution sources, the health situation of plants, etc. using 3D city modelling.  Since this credit can only be fulfilled partially by the CIM application, yet full points are counted for the evaluation.

### 3.1.4. NS Credit: Green spaces:

This credit requires providing green areas within accessible distance to foster the physical, mental and psychological health and welfare of citizens along with improving the environmental quality of the city or community (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). The area of green spaces and their location can easily be demonstrated in a 3D city model (Soon and Khoo, 2017) (Biljecki *et al.*, 2015) (Žiūriene, Mešliūte and Makuteniene, 2006) (Lancelle and Fellner, 2004). The distance of a particular area from a given building is a basic function and can simply be queried in 3D city models, therefore, this credit can be fulfilled using CIM.

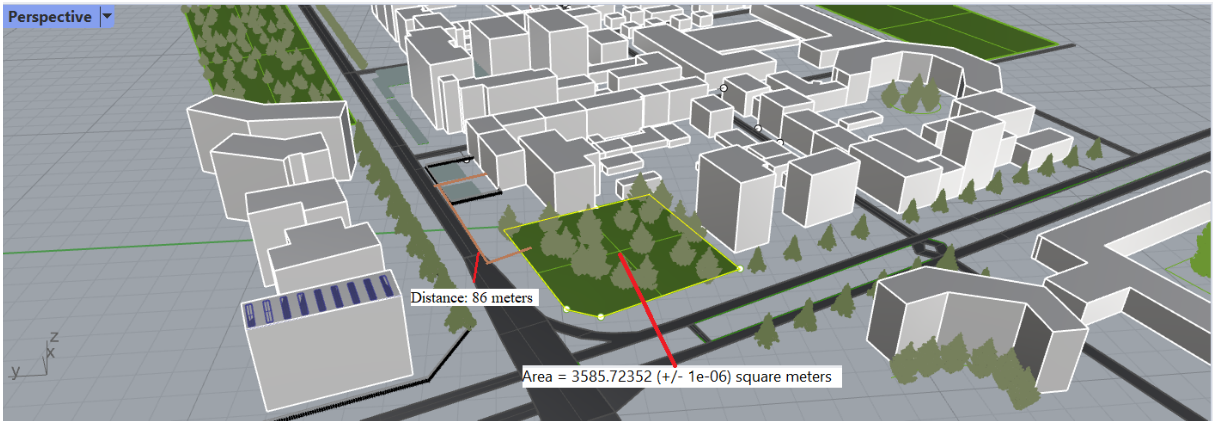


**Figure 17 – 3D city model application for Green Spaces credit compliance (Source: Own work)**

### 3.1.5. NS Credit: Natural Resources Conservation and Restoration:

It involves the perseverance and rehabilitation of the natural resources within the city (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). This credit is quite similar to Green Spaces credit and the location, area, and status of the natural resources can be queried in 3D city models. With most of the governments making BIM compulsory, it can be possible to determine the effect of any new development design submitted for permit certificate on the natural resources stored in the CIM database. The effect of any new development can be viewed in the 3D city model and it can be allowed only if it does not pose any threat to natural resources.

### 3.1.6. NS Credit: Light Pollution Reduction:

This credit demands to minimize light pollution to balance the natural light patterns to reduce negative impacts on public health, ecosystem, sky visibility, and wildlife. There are two pathways to earn this credit; by demonstrating sky glow measurement or limiting sky glow (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). Sky glow measurement can be obtained through specific scales or meters, however, for limiting sky glow, a certain set of standards and adaptation of a lighting ordinance have to be followed. Sky glow sensors can be placed at the desired locations in the residential areas to check compliance. These sensors can be connected with the CIM database through IoT infrastructure to supply real-time data (Bayo, 2016) in the 3D city model.

### 3.1.7. NS Credit: Resilience Planning:

It entails preparing a vulnerability and capacity assessment of the city for climate change, natural and man-made hazards, and extreme events and devising a resilience plan for the city to tackle the above risks (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). These risks, hazards, and extreme events are classified into the following categories: Geo physical such as tsunami, earthquake, etc., Hydrological such as avalanches, floods, Climatological such as extreme temperatures, droughts, wildfire, heat island effect, Meteorological such as cyclones, storms/waves surges, Biological such as diseases epidemics, Social such as emergencies, conflicts, displaced populations, Technological such as cyber-attacks, infrastructure failure, Industrial such as fire, explosion, accidents, Transport such as accidents, Pollution including air and water pollution (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). A 3D city model can aid in resilience planning against events such as flood risk assessment (Ross, 2010), heat island effect (*Modelling the Urban Heat Island and Urban Thermal Stress - ENVI-met*, no date), blast zones (Ross, 2010), pollution source identification (Biljecki, Kumar and Nagel, 2018) and explosion impact analysis (Biljecki, 2017). However, CIM is still limited in conducting a larger scale resilience assessment study accounting for all other factors as well. So, it is safe to say that at the moment, CIM cannot be used to earn this credit.

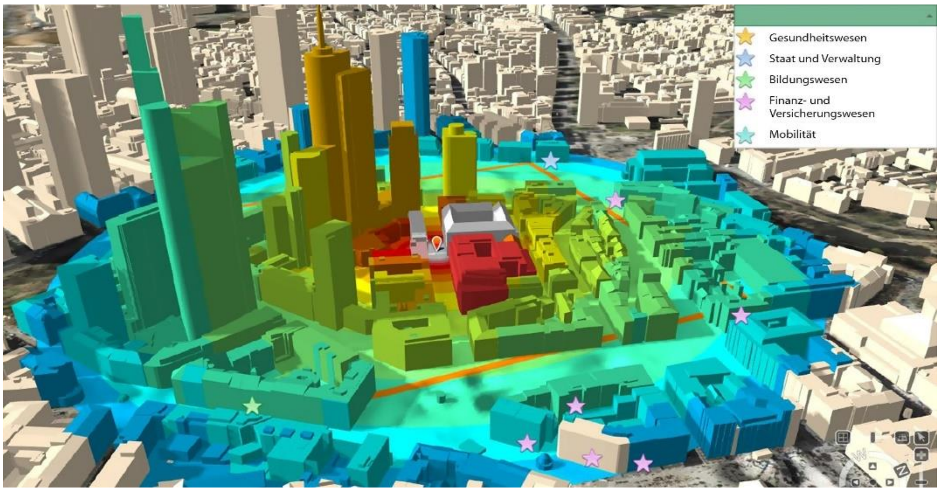


**Figure 18 – Explosion wave propagation and shrapnel impact zone study (Source: Virtual City Systems https://vc.systems/en/products/vc-blastprotect/ )**

### 3.1.8. TR Prerequisite: Transportation Performance:

This prerequisite introduces a requirement to facilitate non-vehicular transportation by encouraging public transport, bicycling, and walking to reduce Vehicle Miles Travelled (VMT) per capita and pollution. VMT can be measured through the non-traffic count, traffic count, or transportation modeling software (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). A 3D city model can be integrated with transportation modelling software to perform different studies such as traffic safety and VMT as well.

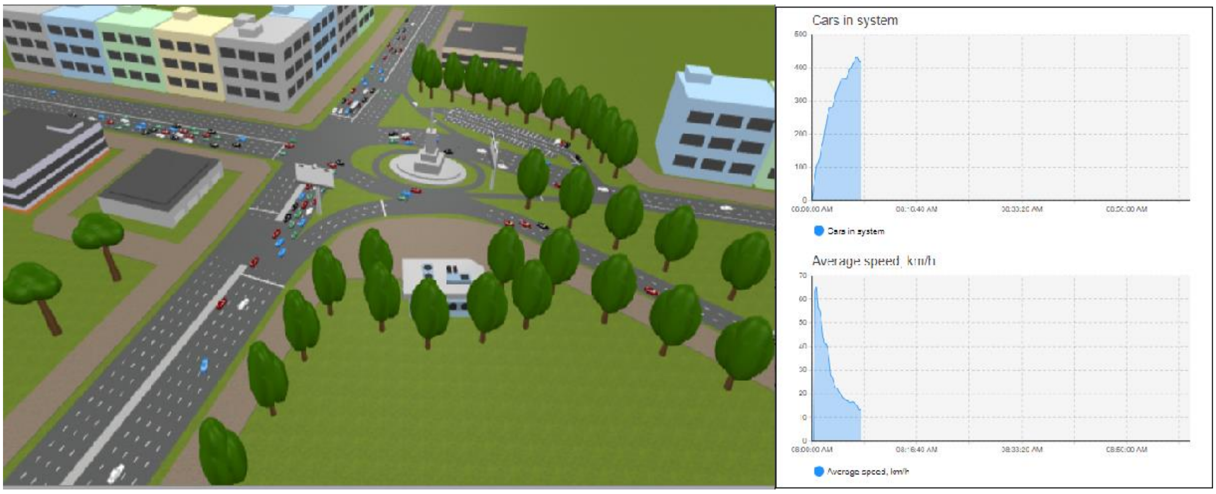


**Figure 19 – Traffic simulation at a roundabout with statistics update (Source: Anylogic Road Traffic Simuation Software https://www.anylogic.com/road-traffic/)**

Smart sensors located at traffic signals connected to the CIM database with IoT network can record traffic data (Bayo, 2016) to perform VMT studies and real-time traffic flow surveys (Schaufler and Schwimmer, 2020) (Biljecki *et al.*, 2015).

### 3.1.9. TR Credit: Compact, Mixed Use and Transit Oriented Development:

This credit demands to promote development in compact, human-scaled, walkable, and universally accessible centers and neighborhoods that connect to public transit and offer diverse uses and services (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). The location and distance of diverse uses and transit stops can be evaluated easily in a 3D city model. Also, the universal accessibility of compact and complete centers (CCC) can be identified by the 3D city model. For instance, the Urban Modelling Interface (umi) tool developed by Sustainable Design Lab of Massachusetts Institute of Technology (MIT) allows calculating the mobility score by evaluating the accessibility extent of a neighbourhood or a community (*Urban Modeling Interface | MIT Sustainable Design Lab*, no date).

### 3.1.10. TR Credit: Access to Quality Transit:

This credit warrants the city government to encourage the population to take diverse transportation means other than their motorized vehicles by deploying safe and comfortable transit stops and frequent transits. The percentage of the population commuting to work and other places with different kinds of transport options has to be calculated along with any of the following approaches.; ensuring the quality of transit facilities, providing intermodal connectivity of three or more transportation modes at the same station; ensuring the frequency of trips must meet the criteria set for weekday and weekend trips (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). The calculation of people commuting to work with different modes of transportation can be carried out by placing cameras or infrared (IR) sensors at the desired locations such as bus stops, in the cycling track, footpath, sidewalks, roads, etc (Zheng and Mike, 2012) (Bayo, 2016). These sensors can be integrated with the CIM database through IoT infrastructure. The quality and condition of transit stops can be ascertained by visual analysis as well. Global Positioning System (GPS) trackers placed in public transport do not only allow to receive real-time vehicle location, speed, direction but they can be tweaked to calculate the trips of a certain public transport vehicle at a certain stop.

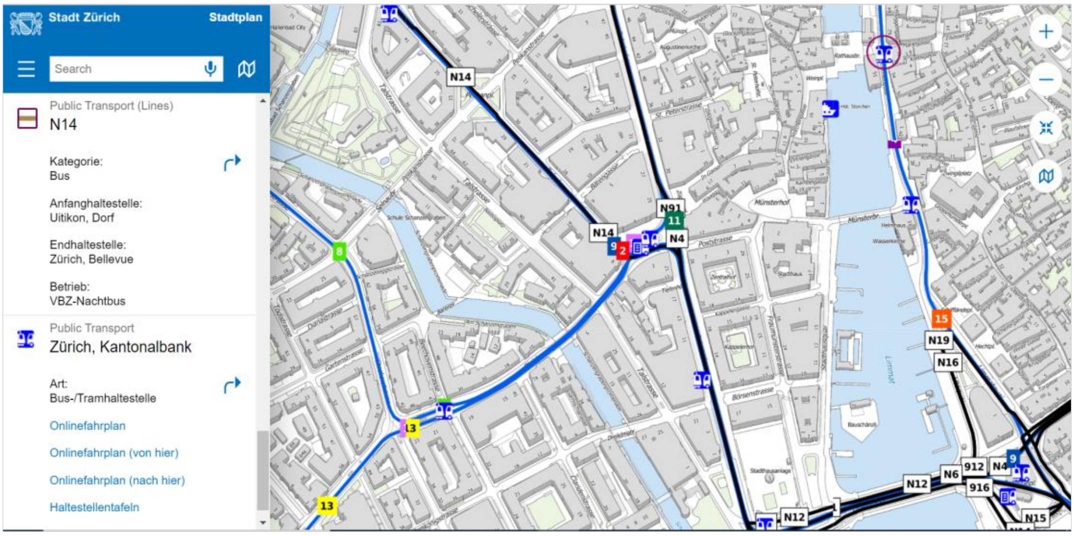


**Figure 20 – Transit locations in 3D city model of Zurich (Source: Zurich Municipality website)**

### 3.1.11. TR Credit: Alternative Fuel Vehicles:

Alternative fuel vehicles credit demands to facilitate alternative fuel consuming transportation to reduce the usage of conventional fossil fuel vehicles by providing charging points and alternative fuel stations (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). While creating a 3D city model, the electric vehicle charging points are modelled that are located outside, however, for charging stations in a covered parking area such as a basement parking needs to be in LoD 4 through BIM models, however, every building does not have BIM models in a city but any charging points can inside a building be attributed to that building. It is also possible to query the location and number of electric vehicle charging stations in a city (*Virtual Singapore*, no date b) and then be compared against the number of residents to demonstrate compliance to earn this credit.

### 3.1.12. TR Credit: Smart Mobility and Transportation Policy:

The requirement in this credit is to implement smart technologies and strategies to provide smart, efficient, and adequate transportation to the citizens. There are several strategies and technologies to adopt to earn this credit such as equipping transit stations with Passenger Information System (PIS), automated speed enforcement, traffic surveillance with CCTVs, placing GPS/GPRS systems on public transport, signal synchronization, and transit signal priority, automated and integrated ticketing system, real-time parking management system, electronic toll collection, and radio frequency identification (RFID) for logistics and/or public transport vehicles (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). Adoption of any two aforementioned technologies will fulfill this credit.

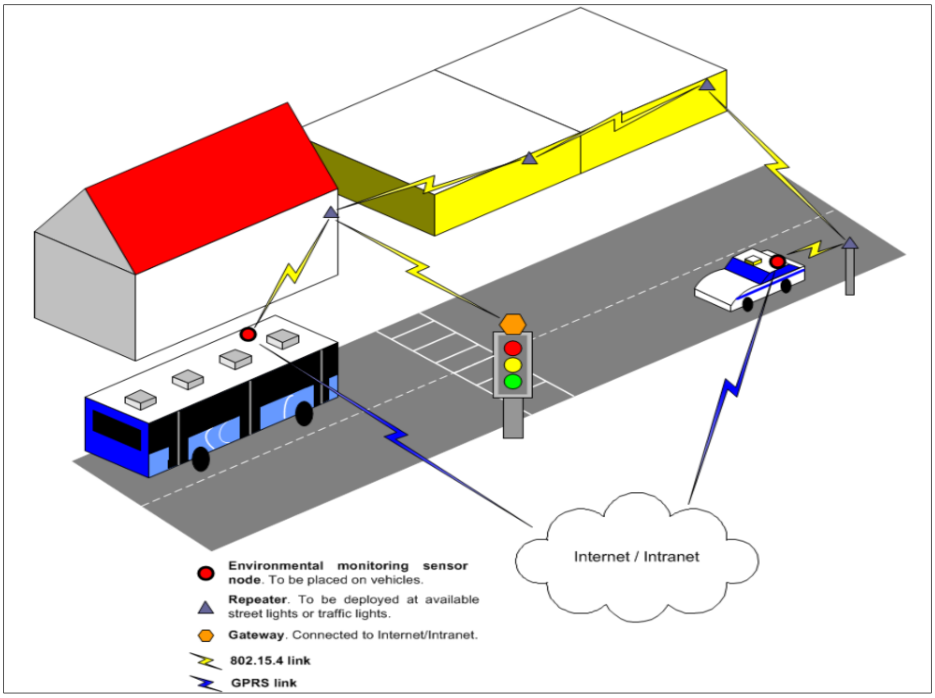


**Figure 21 – Connection schema of sensors placed on moving vehicles (Source: www.smartsantander.eu,** (Bayo, 2016)**)**

Many public transport vehicles have GPS/GPRS trackers to relay real-time positions. Also, for on-ground transit stops, CCTVs and PIS can be visible in a 3D city information model. RFID and parking space status responses based on IoT can be forwarded to the CIM database with embedded sensors in parking spots (Bayo, 2016). Therefore, a dynamic 3D city model can track and ensure the implementation of smart mobility and transportation policy.

### 3.1.13. TR Credit: High-Priority Site:

The purpose of this credit is to conserve historic structures and sites and encourage growth and redevelopment on brownfields, infill sites, and other priority locations. There are three approaches to demonstrate compliance, viz., rehabilitation, preservation, or restoration of any historical building, development on a brownfield or similar site, or focusing on regrowth in high-priority redevelopment areas (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). The attributes of the sites, buildings, and areas can be stored (Egusquiza *et al.*, 2018) in the CIM repository and queried at any time which is conducive to the preservance of historic buildings and prioritization of the development on brownfields or infill sites. The application of CIM can prove beneficial for this credit as well.

### 3.1.14. WE Prerequisite: Water Access and Quality:

This prerequisite emphasizes providing equitable access to clean drinking water, sanitation services to all the population and prevent pollution from sewage and stormwater discharge (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). A 3D city model can hold water and wastewater infrastructure information (Batty *et al.*, 2000) (Ross, 2010) (Schrotter and Hürzeler, 2020) (Kutzner and Kolbe, 2016) (Biljecki, Kumar and Nagel, 2018). The access to clean drinking water and sanitation services can be checked visually or another approach can be used such as creating nodes within each building and comparing the number of nodes connected to water and sanitation pipelines with the total number of nodes (the no. of buildings). For determining the level of pollution in wastewater, wireless sensors (Bayo, 2016) can be rolled out to relay data to the CIM database which can be viewed or queried in real-time using IoT.

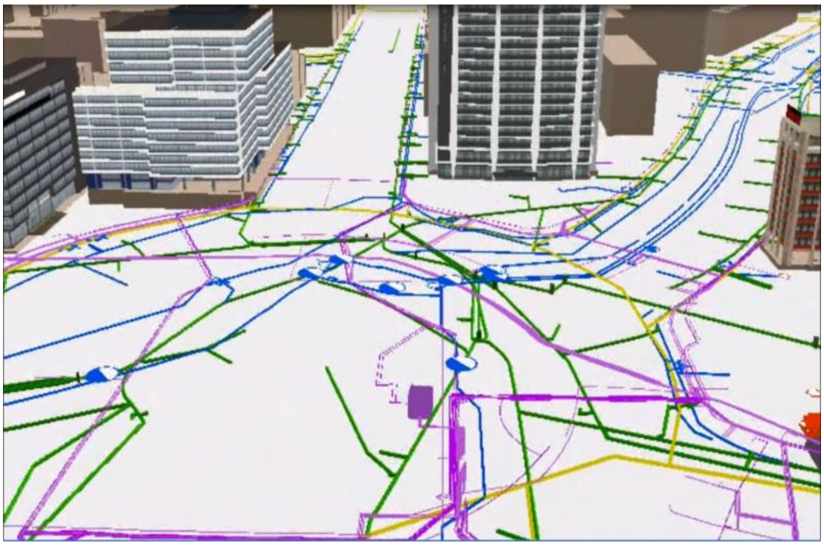

**Figure 22 – Underground utility network in Berlin (Source: SIMCAS 3D)**

### 3.1.15. WE Prerequisite: Water Performance:

This credit requires to demonstrate water management by reducing water demand and consumption per capita in the city. To fulfil this credit, domestic water consumption is to be recorded by excluding agricultural irrigation, golf course irrigation, livestock, aquaculture, mining, or thermoelectric generation (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). With the growing population especially in urban areas, it is indispensable to track water consumption through smart meters and record it in a central database. A dynamic 3D city information model can hold this information (Lafioune and St-Jacques, 2020) and it can be investigated with its relation to other factors modelled in the city.

### 3.1.16. WE Credit: Integrated Water Management:

It requires to decrease freshwater consumption by an integrated water management process to exhibit that the ratio of water withdrawals for human use to the total freshwater available is below 0.2. It includes the preparation of water availability assessment, water demand record, and evaluation of total water supply (fresh water and alternative water) (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). A 3D city model can be used for determining the total demand and supply to the city as well as consumption data of individual buildings with the application of smart meters, however, recording alternative water supplies such as greywater or harvested rainwater which mostly exist off-grid is very complicated. Therefore, supplying all the data required for this credit to the CIM database seems very difficult.

### 3.1.17. WE Credit: Stormwater Management:

This credit entails implementing stormwater management strategies to avoid flood risks and associated damages and to recharge groundwater. It involves the provision of bioretention and infiltration services and management of rainfall by imitating the natural site hydrology process. There are 2 pathways to adopt to fulfill the requirements of this credit such as reporting flooding incidences or reporting the detailed description of stormwater infrastructure, or demonstrating that 35% area under the city government has designated green stormwater infrastructure providing interlinked bioretention and infiltration services (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). Flood risk simulations can be carried out in a 3D city model (Ross, 2010) (Žiūriene, Mešliūte and Makuteniene, 2006). Also, green stormwater infrastructure can be modelled under vegetation context in the 3D city model and assigned relevant attributes to locate these areas in the model.

### 3.1.18. WE Credit: Smart Water Systems:

This credit can be earned by implementing smart technologies to enhance the operational efficiency of water management systems. It requires water auditing or automating the water supply network and its management (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). The automation of water supply infrastructure for data collection, tracking, and monitoring can bridge the gap between water data collection and the CIM database (Batty *et al.*, 2000) (Ross, 2010) (Schrotter and Hürzeler, 2020). A 3D city model can act as a platform to store, track and query water network data.

### 3.1.19. EN Prerequisite: Power Access, Reliability and Resiliency:

This prerequisite lays down the requirement of providing power supply to all sectors of the population, implement non-stop monitoring protocols, and ensure backup power availability for essential, critical, and emergency services in case of a disaster or power outages (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). Modelling utilities including electrical supply is an important element in CIM and it is possible to check visually the connection of electricity network with buildings (Batty *et al.*, 2000) (Žiūriene, Mešliūte and Makuteniene, 2006). Another method is to create an algorithm to assign a node at the connection of buildings and electricity supply and comparing the number of nodes with a total number of buildings to evaluate if all sectors of the population are getting power supply or not. Furthermore, automatic power monitoring system feedback can be embedded into the CIM database through IoT (Shipman and Gillott, 2019) (Francisco, Mohammadi and Taylor, 2020) to view real-time power data. However, for backup supplies in critical or emergency services, mostly generators or backup systems are placed inside the buildings therefore, a 3D city model with LoD 4 (with BIM) is desired to view it.

### 3.1.20. EN Prerequisite: Energy and Greenhouse Gas Emissions Performance:

It requires the preparation of an emissions inventory to promote energy management and grow towards a zero-energy and emissions city is required in this prerequisite. It demands to measure annual energy consumption and Greenhouse Gas (GHG) emissions for the city (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). City energy modelling can be carried out to estimate the overall energy consumption and GHG emissions of the city (Biljecki, 2017). For individual buildings, a detailed assessment can be performed through BIM. Smart energy meters connected with the CIM database through IoT can communicate actual consumption data to the model to compare with the energy modelling results.

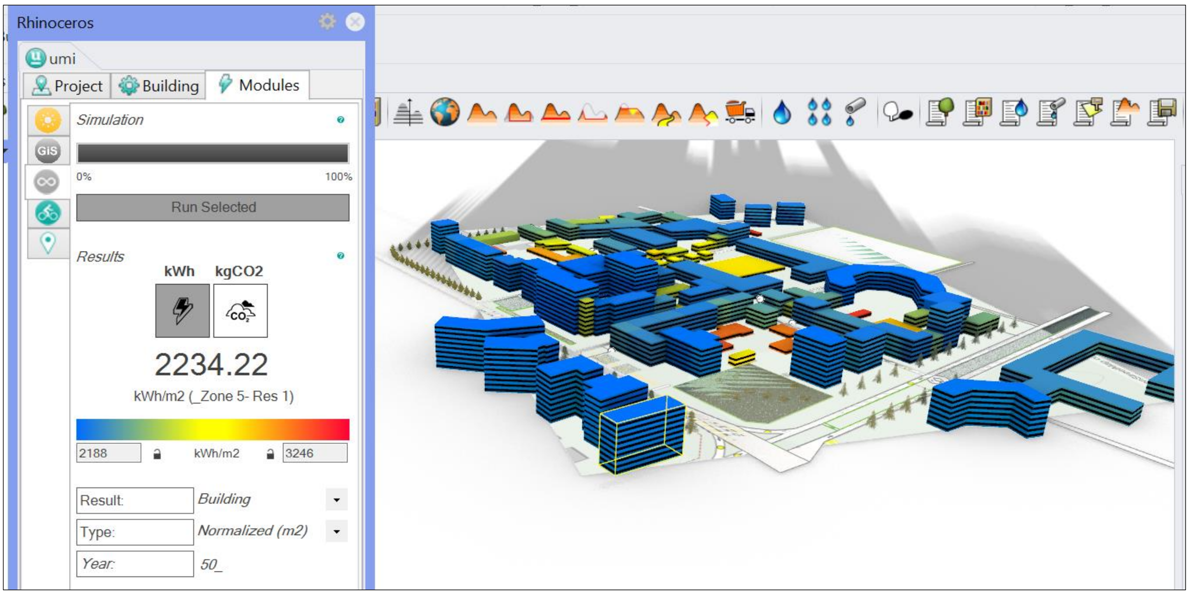


**Figure 23 – Energy and CO2 emission results for a building in the modelled neighbourhood with umi (Source: Own work)**

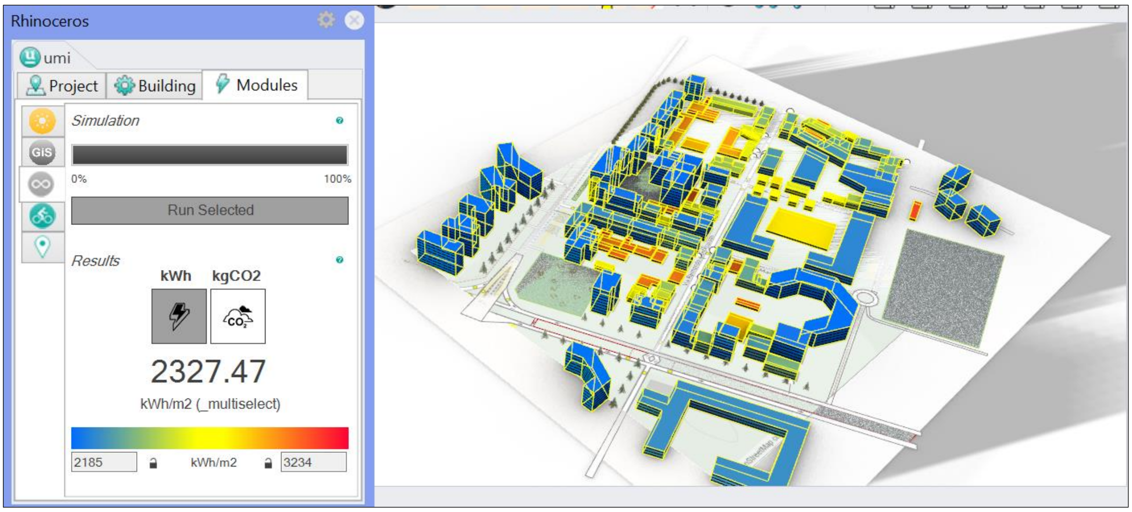


**Figure 24 – Energy-simulation results for the modelled neighbourhood with umi (Source: Own work)**

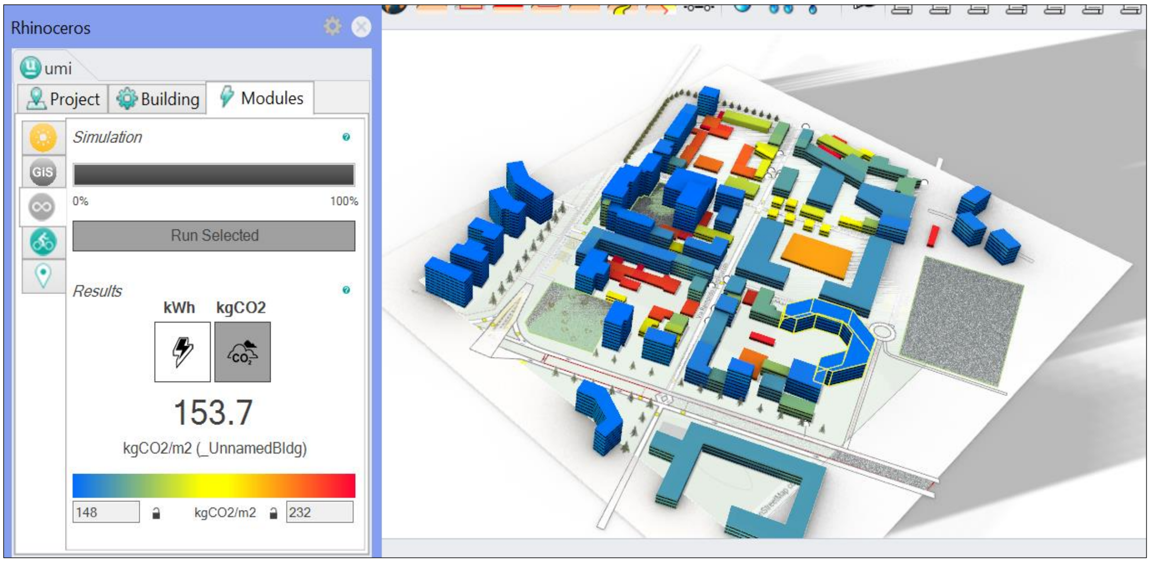


**Figure 25 – CO2 emission results for the modelled neighbourhood with umi (Source: Own work)**

### 3.1.21. EN Credit: Energy Efficiency:

This credit involves the installation of energy-efficient fixtures and devices in the city to improve energy efficiency by placing energy-efficient street lamps, pumps deployed for water supply, drainage, and treatment, and/or incorporating a district heating/cooling system (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). It is not possible to check the specifications of every street light or water pump, therefore, 3D city models cannot be utilized for this credit.

### 3.1.22. EN Credit: Renewable Energy:

It is required to promote renewable energy supply to reduce negative impacts linked with fossil fuel energy. One or more sources can be opted to procure renewable energy (such as solar PV, wind, geothermal, micro or small-scale hydro, or biomass) (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). At the moment, research studies have indicated that 3D city models are an effective tool to assess the potential of solar energy (Lafioune and St-Jacques, 2020). A 3D city model can be used to determine the solar irradiance at a city level scale and establish the optimal locations for solar panel placement since the location, geometry, orientation, and obstructions to the building influence solar light (Yousuf *et al.*, 2017). Some studies have also focused on wind flow (Soon and Khoo, 2017) which can be upscaled to evaluate the wind energy potential. A simulation on solar irradiance and solar energy potential has been conducted with umi in Rhino which is shown in the figure below. However, to monitor the supply of energy generated from solar panels, the smart meters can be integrated with the CIM database to feed live energy generation data to the 3D city model.

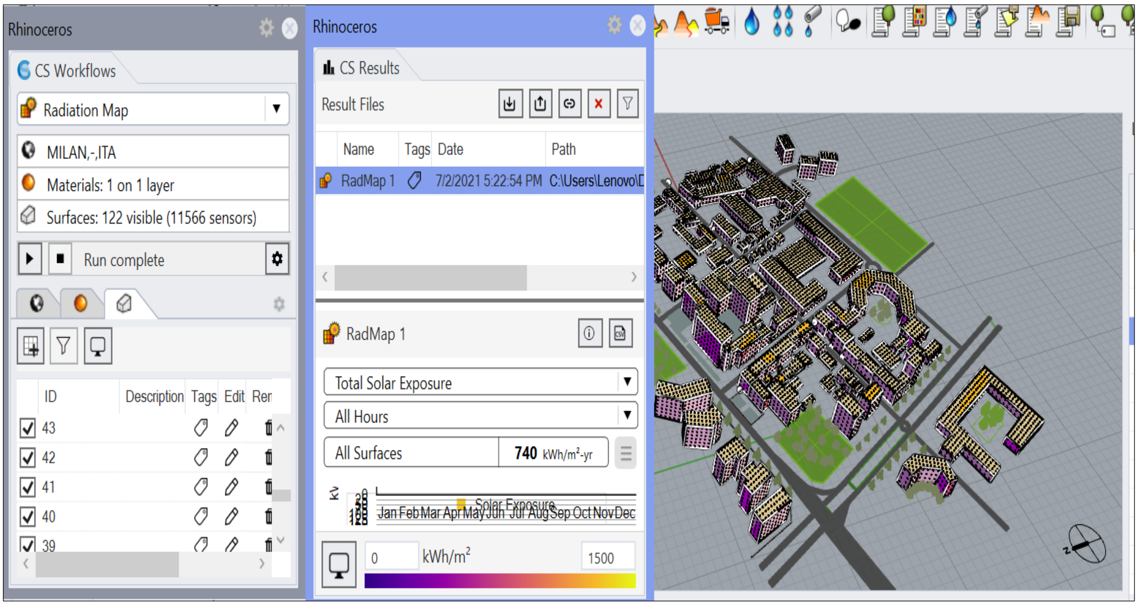


**Figure 26 – Solar exposure simulation conducted on the modelled neighbourhood with umi in Rhino (Source: Own work)**

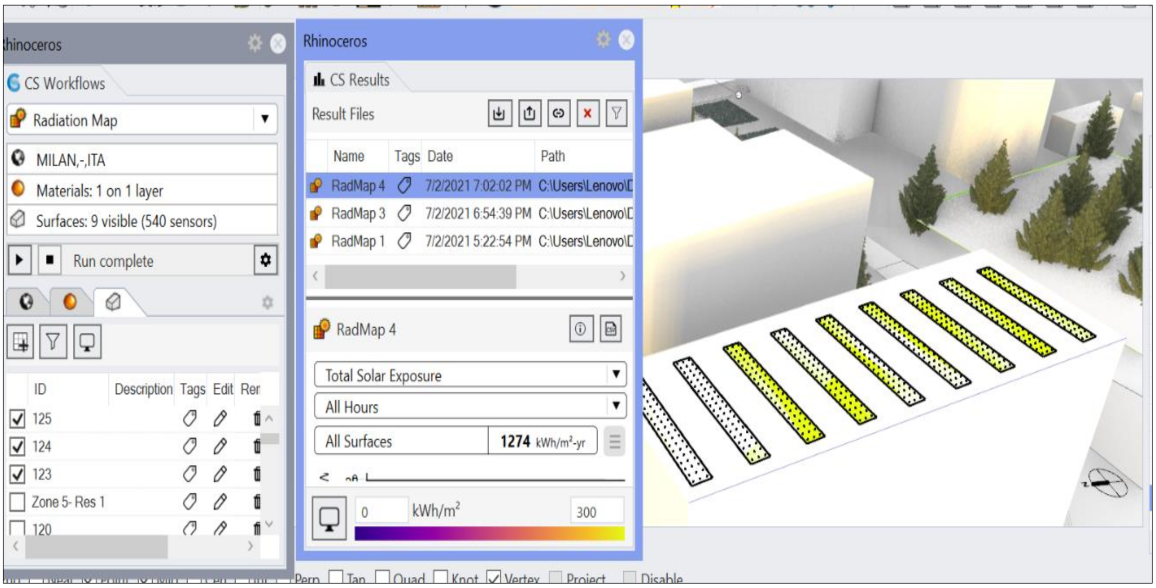


**Figure 27– Solar energy potential simulation conducted on a building in the modelled neighbourhood with umi in Rhino (Source: Own work)**

The solar energy generation potential analysis also generates a graph to view the solar energy generation potential every month throughout the year as shown below:

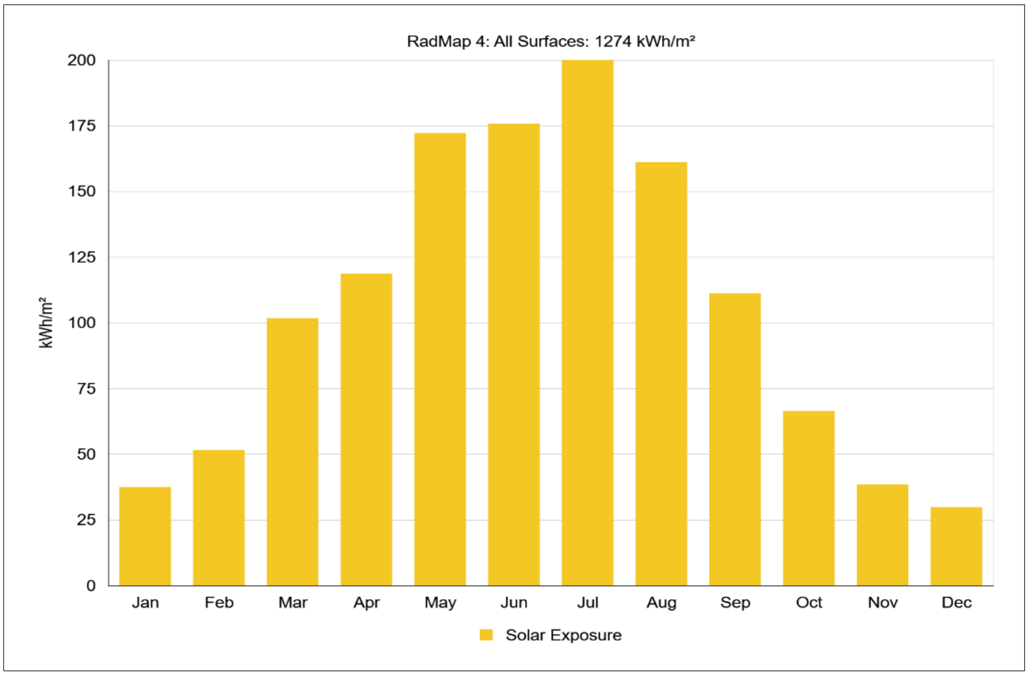


**Figure 28 – Monthly solar energy generation potential (Source: Own work)**

3D city modelling enables analysing the daylighting potential of existing buildings and the impact of new development on existing buildings which can aid in reshaping, redirecting, or reorienting the buildings.

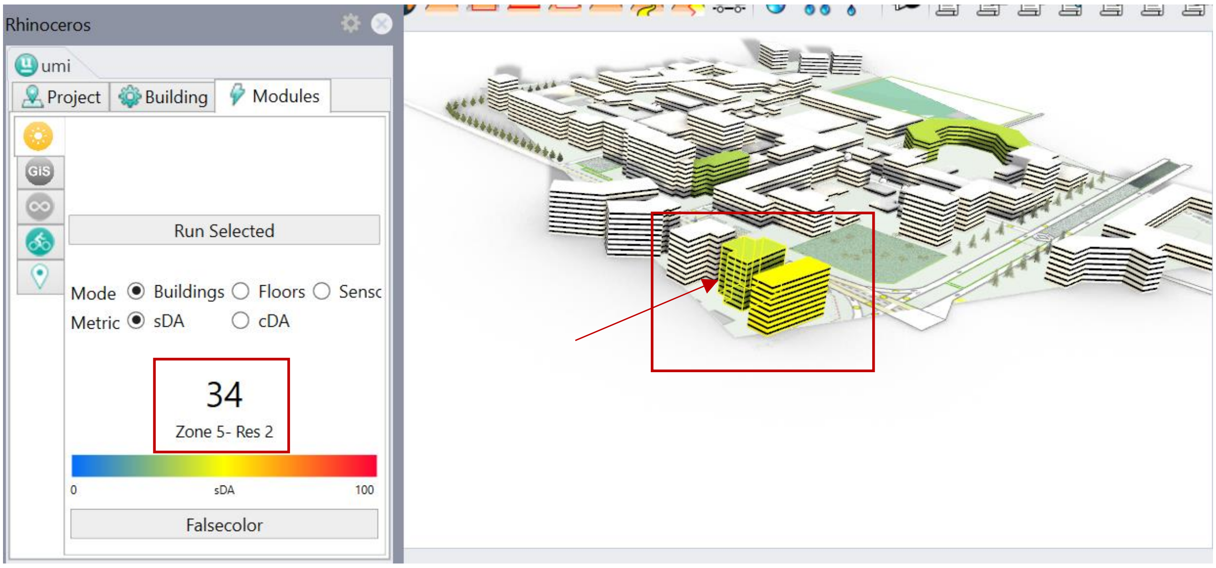


**Figure 29 – Spatial Daylight Autonomy (sDA) of a building influenced by neighboring building (Source: Own work)**

The current sDA is 34 of the building due to the shadow of the building next to it. 3D city modelling allows to investigate different scenarios such as changing the geometry of the building or changing its location to visualize and analyse the daylighting values.

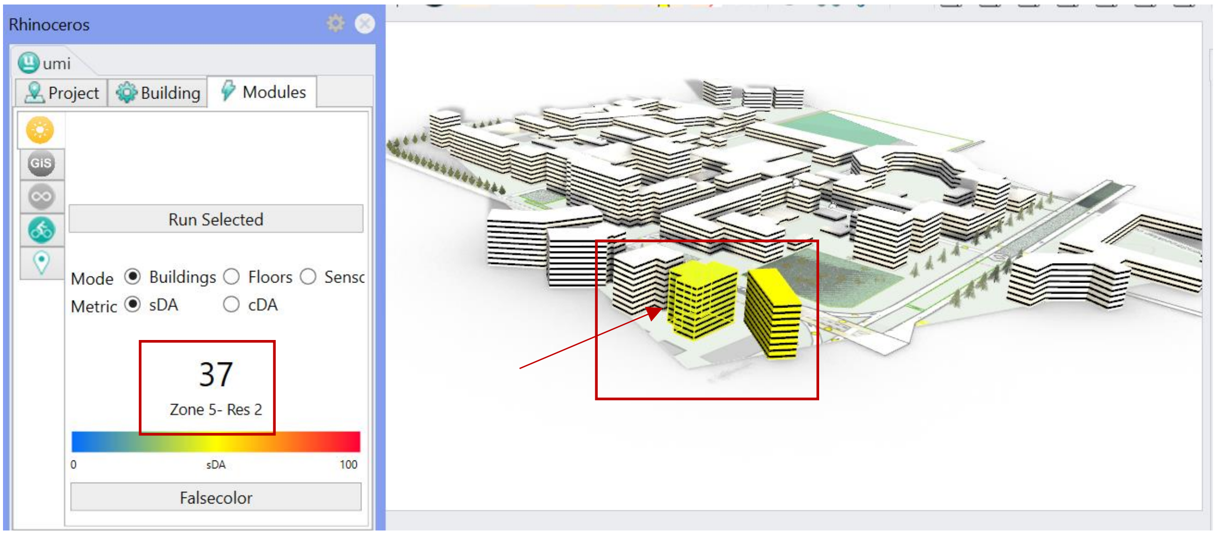


**Figure 30 – Spatial Daylight Autonomy (sDA) of a building influenced by neighboring building after changing the position of the neighbouring building (Source: Own work)**

It is illustrated that sDA of the building is now 37 which was 34 before changing the position and orientation of the neighboring building. 3D city modelling allows performing assessments to determine the optimal positioning of the building for daylighting at a city scale.

### 3.1.23. EN Credit: Low Carbon Economy:

This credit seeks to encourage a low carbon economy by disintegrating economic growth from greenhouse gas emissions. This credit can be fulfilled by reporting GHG emission intensity and/or reduction in GHG emission intensity. GHG emission intensity is calculated by dividing the total GHG emissions of a city by its total Gross Domestic Product (GDP) (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). An estimate of GHG emissions can be made by simulating a 3D city model, however, it is not possible to consider the whole urban metabolism in a 3D city model since all the inflows, outflows, and consumption are not recorded accurately. Therefore, it is very improbable that this credit can be fulfilled by CIM.

### 3.1.24. EN Credit: Grid Harmonization:

This credit requires to promote user participation in energy use optimization to augment the operational efficiency of the energy system. There are three approaches to comply with this credit; providing access to dynamic pricing for load management, setting in place a demand-response system, or adopting a net metering and interconnection policy (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). However, these requirements cannot be checked through a 3D city model at the moment.

### 3.1.25. MR Prerequisite: Solid Waste Management:

This prerequisite necessitates providing 100% coverage to all city populations or buildings by waste management facilities and prepares a solid waste management plan to handle waste efficiently (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). A 3D city model cannot be used to check the coverage extent of waste management facilities, unlike water, sanitation, and power access. The waste containers can still be installed with sensors relaying the waste-fill status (Bayo, 2016), however, it is not necessary that every building has separate waste containers like separate power/water connections. If every building has separate waste containers or the coverage area of a particular waste container is specified then the sensors placed at each waste container may feed this data to the 3D city model. However, at the moment, it might not be possible to apply for CIM for this credit.

### 3.1.26. MR Prerequisite: Waste Performance:

The Waste Performance prerequisite sets the requirement to promote waste management by diverting maximum waste from landfills and progress towards a net zero-waste city. The total municipal solid waste generated in metric tons per year per capita is compared with total municipal solid waste diverted from landfills or incineration (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021) The municipal authorities are normally in the possession of this data and it can be uploaded to the CIM database and queried by any relevant entity to view the waste performance of the city; even public should be able to view the performance of the city waste management system. CIM can hold this information as an attribute to the city (Dantas, Sousa and Melo, 2019). The points depend on the diverted waste, however, the CIM model can hold all the information, and maximum points can be achieved as well.

### 3.1.27. MR Credit: Special Waste Streams Management:

This credit has the requirement to adopt strategies to handle special waste streams by diverting them from landfills and incinerators and recovering and recycling reusable materials (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). CIM may be applied for this credit as keeping a record of all waste generated, diverted, and recycled is (usually) obligatory for waste management authorities and it can be uploaded in the CIM database (Dantas, Sousa and Melo, 2019) to be accessed by the relevant city stakeholders and entities.

### 3.1.28. MR Credit: Responsible Sourcing for Infrastructure:

It is required to promote materials and products for which life cycle assessment has been performed and their extraction is performed responsibly to fulfil this credit (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). This credit targets every material used in the city. However, even focusing on buildings would be difficult to earn this credit. Since the new buildings can have all the required information of the materials, however, old buildings are very unlikely to have this information. Therefore, it would not be possible to record every building materials’ data in the CIM database.

### 3.1.29. MR Credit: Material Recovery:

It is needed to develop mechanisms to recover materials from waste streams and collect and return these materials to the manufacturer for fulfilling this credit (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). The development of mechanisms and plans are descriptive and their implementation cannot be uploaded in the CIM platform. Policy checking relies on respective authoritative bodies and a city model cannot be used to validate a policy. Therefore, a 3D city model is unlikely to be used to fulfil or contain this information.

### 3.1.30. MR Credit: Smart Waste Management Systems:

This credit can be fulfilled by implementing smart solutions or strategies for waste management to handle at least 20% of the waste generated. Different strategies can be adopted for this purpose which includes the application of digital solutions such as an automatic vacuum waste collection system, smart bins with sensors, image-based or weight-based trash cans sensors, and intelligent route optimization for waste collection (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). All these technologies can be deployed and the CIM database can collect relevant data. Underground pneumatic tubes for waste collection can be modelled in the 3D city model as a utility network (Kutzner and Kolbe, 2016), and sensors placed in trash bins can disseminate the data to the CIM database about its fullness status. Furthermore, waste vehicles are also equipped with GPS/GPRS feeding location, speed, the direction of movement (Bayo, 2016). The data from waste truck trackers and sensors installed in the trash bin can intimate the nearest waste truck when it is full and the CIM database can define the optimal route for emptying it.

### 3.1.31. QL Prerequisite: Demographic Assessment:

Demographic assessment prerequisite requires to prepare a comprehensive narrative of population demographics and housing features of the city including a brief history of development, age cohorts, racial/ethnic composition, housing market analysis, and develop an interactive map encompassing residential density, public services such as parks, fire stations, police stations, libraries, etc., and demographics indicators such as minority population, low-income population, under age 5, above age 64, etc. (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). A 3D city model is able to contain metadata related to a building which may comprise of total residents, number of dwellings, etc., and the location of public offices and services can be determined through a 3D city information model. The demographic indicators are also available publicly based on settlements especially in Europe (*Overview - Population and demography - Eurostat*, no date). This data can be stored into CIM database as well to develop an integrated web portal of city information through different ways, e.g., developing Application Domain Extensions (ADEs) for CityGML (Biljecki, Kumar and Nagel, 2018), or stored into the model while developing the model as metadata, etc.

### 3.1.32. QL Prerequisite: Quality of Life Performance:

This prerequisite necessitates to track and evaluate parameters related to the living standards of all the city population including education, equitability (gross rent, gini coefficient), prosperity (median household income, unemployment rate), and health and safety (median air quality index (AQI), air quality days unhealthy for sensitive groups, violent crime) (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). These indicators can be stored into CIM database as city attributes since it is not relevant to a certain building but the overall performance of the city. Reporting these parameters to the CIM database will render the city information model as the integrated platform of city information.

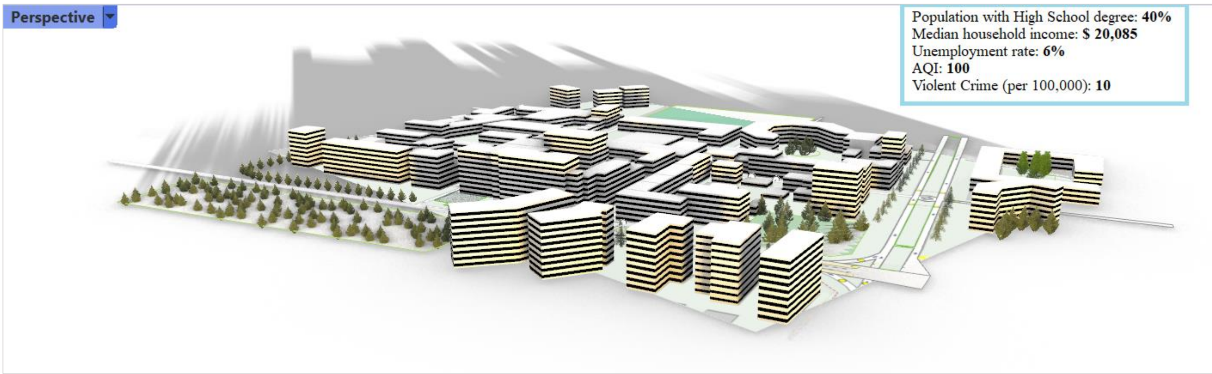


**Figure 31 – A schematic representation of the required indicators information in a 3D city model**

### 3.1.33. QL Credit: Trend Improvements:

This credit entails demonstrating improvements in up to 4 following parameters related to the living standards of all populations; population with a high school degree, graduation rate, small businesses, unemployment rate, poverty rate, percentage of household incomes meeting the living wage standard, violent crime, asthma rate, hypertension, and obesity rate (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). The same logic can be applied here as per QL Prerequisite: Quality of Life Performance in the bid to treat the CIM database as the unified and integrated platform for information recording, sharing, and exchanging besides visual 3D manifestation of city objects (Dantas, Sousa and Melo, 2019).

### 3.1.34. QL Credit: Distributional Equity:

This credit lays out the requirement to promote equitable economic progress and promote access to community services. This credit can be fulfilled by following any pathway out of 4 approaches. The first three options correspond to sharing and demonstrating information like previous credit, however, option 4, Access & Proximity, requires to manifest that community facilities, such as parks, recreation areas, libraries, schools, and healthful retail food outlets are as accessible to low-income residents as to the general community. The walkability distance is based on the density of the low-income area (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). This can simply be done in a 3D city model by marking the accessibility (walkability distance) of these specific places from low-income areas. The density can be checked by referring to the metadata of a building to determine the number of dwellings in the very building. The area categories (low-income, medium-income, high-income) can also be stored in the CIM database as an additional attribute that can be queried when needed and to represent the associated areas.

### 3.1.35. QL Credit: Environmental Justice:

Environmental justice necessitates tackling conditions that may be conducive to neighborhoods or populations being influenced by environmental pollutants. It requires identifying the specific sections of the community such as women and/or children, low-income groups, specific neighborhoods, or sociocultural groups who face the disproportionate influence of human health or environmental effect and also locate the priority areas with the highest percentage of historically overburdened populations, the highest concentration of environmental pollutants or polluters, or where environmental regulations violations occur or have been occurred, etc. (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). The identification of priority sections of community and areas are based on assessments, studies, and surveys and it may be reported to the CIM database especially the areas with pollution or polluters through sensors or where environmental violations have occurred or occurring, however, presentation of all the data is not straightforward and CIM might not be a suitable platform for it.

#### 3.1.36. QL Credit: Housing and Transportation Affordability:

This credit requires furnishing a suitable and diverse supply of location-efficient and affordable housing options for all the residents. It involves the provision of high-quality homelessness services on short-term along with other 4 approaches to select from such as formulating a comprehensive housing policy, demonstrating housing and transportation costs percentage, exhibiting affordable housing production rate, and/or showing the number of subsidized affordable housing units (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). Housing affordability is one of the major concerns for city governments all around the world (Li, Cheung and Shoaib, 2018). The aforementioned statistic can be saved and accessed in the CIM database, however, the provision of high-quality homelessness services on a short-term basis cannot be illustrated in a 3D city model which is an obligatory part of this credit.

#### 3.1.37. QL Credit: Civic and Community Engagement:

This credit underpins encouraging an inclusive and socially integrated community and supports their participation in local decision-making by exhibiting both high-tech and high-touch on-going engagement techniques for the community which allows all the residents to participate in the decision-making process. Furthermore, it demands to fulfill any two of the following options; diversity in appointment to the local advisory board, manifesting through a survey that 51% or more residents believe they can have a positive impact on their community, exhibiting through a survey that 80% of residents report positive levels of neighborhood integration, and showing that 30% of residents in large settlements or 35% of residents in small or mid-sized settlements volunteered (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). A 3D city model-based mobile app or web portal can allow citizens to record their feedbacks, comments, and notes and also report incidences such as broken benches, abandoned city bikes, etc., with spatial context (Bayo, 2016). A 3D city model can give citizens a better pictorial representation so they can assess the impacts of any potential development on the neighbourhood with simulations such as noise pollution mapping, crowd movement patterns, etc (*Virtual Singapore*, no date b). However, the development of a 3D city model does not guarantee the participation of citizens in the decision-making process despite it being a digital engagement tool but it depends on their inclusion in policy-making and decision-making by the city administrative bodies.

#### 3.1.38. QL Credit: Civil and Human Rights:

This credit demands to adopt a mechanism that ensures the civil and human rights of all people is fundamental. It calls for promoting an unbiased and free life quality pertinent to employment, housing, and public accommodations on the grounds of ethnicity, sex, race, color, religion, nationality, disability, age, sexual orientation, political inclination, and gender identity or expression, etc. (*LEED v4.1 CITIES AND COMMUNITIES EXISTING*, 2021). A 3D city model is not able to uphold or address the aforementioned objectives since it necessitates developing a policy-based strategy and its implementation which cannot be supported by CIM.

### 3.2. CIM applications for sustainability:

While modelling a 3D city model or developing a database for it or even contemplating on what information to be included, there needs to be a pertinent and quantifiable set of parameters that can be incorporated in the CIM data structure to evaluate the performance of the city against the sustainable urban development benchmarks. CIM-based analysis of LEED for cities and communities reveals a list of prerequisites and credits fulfillable by using 3D city models and its data infrastructure. These parameters (prerequisites and credits) define the extent of sustainability in a city or urban settlement by quantifying it into a category of score benchmark (with certified level as the lowest and platinum level as the best) to assess the performance extent of the urban settlement. This list constitutes a set of information, rules, standards, data collection methods and points, assets, people, technology, devices, etc., which needs to be accounted for while developing a CIM platform. The data which should be considered while modelling a city aligned with sustainability evaluation can be divided into different modules as presented in Figure 32. The modules required can be supplemented with additional information based on regional context and requirements,

| **3D City Model** | | | | | |
|---|---|---|---|---|---|
| **Building module:** | **Nature module:** | **Services module:** | **Transportation module:** | **Life Quality module:** | **Sensors module:** |
| - historical buildings<br>- ahistorical buildings<br>- public buildings<br>- private buildings<br>- under construction buildings<br>- commercial buildings<br>- residential buildings<br>- industrial buildings<br>- other buildings | - vegetated spaces<br>- city parks<br>- water bodies<br>- green roofs<br>- deserts/arid land<br>- infiltration areas<br>- rainwater retention areas<br>- wildlife habitat<br>- wetlands<br>- forests<br>- public seating areas<br>- vacant lots<br>- playgrounds<br>- other ecological spaces | - water network<br>- Gas/DH lines<br>- Telecommunication lines<br>- electricity lines<br>- miscellaneous pipes<br>- light poles<br>- city furniture<br>- garbage containers<br>- decorative features | - roads<br>- railways<br>- underground tracks<br>- cycling paths<br>- sidewalks<br>- parking spaces<br>- transit stops | - demographics<br>- average income<br>- crime rates<br>- areas of deprived population<br>- other relevant information | - smart water meter<br>- smart energy meter<br>- RFID<br>- GPS/GPRS<br>- CCTV<br>- lighting sensors<br>- water quality sensors<br>- air quality sensors<br>- traffic flow sensors<br>- smart trash bin sensors |

**Figure 32 – Recommended information to be modelled for sustainability evaluation**

This analysis serves as a foundation for the data architecture of a 3D city model by formulating a tangible approach towards the development of a 3D city model and its data management platform. Considering the data infrastructure requirements of a sustainability-focused 3D city model, a taxonomy has to be developed to categorize CIM applications for simplification and a clear plan-of-approach.

#### 3.2.1. Taxonomy of 3D city models:

Biljecki et al. has developed a taxonomy of use cases of 3D city models based on visualization aspect i.e., non-visualization use cases and visualization-based use cases (Biljecki *et al.*, 2015). This classification seems to be developed on the computational and analysis aspects. For instance, for energy analysis, a user does not have to necessarily see the building/s visually contrary to lighting simulations or visibility analysis. In this study, a taxonomy for 3D city models is propounded based on their data collection and modelling approaches i.e., static 3D city models and dynamic 3D city models, and this taxonomy is reflected in the use cases as well.

3.2.1.1. Static 3D city modes:

A static 3D city model, according to the aforementioned data collection approach-based taxonomy, is a city model which is developed once using aerial lidar, photogrammetry, or any other technique and updated later on with new information or city objects and it has no continuous real-time or near real-time data feeding. A static 3D city model is just a virtual representation of the city and can be applied for various stand-alone analyses without any automated or semi-automated information sharing a connection with any device/s (sensors) installed in the real-world such as shadow analysis, daylighting analysis, energy assessment, flood risk assessment, microclimate analysis, etc. The developed taxonomy can be applied to CIM-based analysis of LEED for cities and communities and those parameters can be easily identified which do not need a digital connection between a 3D city model and ICT devices placed in the outside world.

**Table 4 – The applications of static 3D city models aligned with LEED parameters**

| LEED Parameter | Possible Points | Static 3D City Model Applications |
|---|---|---|
| **NS Prerequisite: Ecosystem Assessment** | n/a[1] | Modelling and identification of landscapes, vegetation, water bodies, etc., and flood risk assessment can be carried out in a static 3D city model. |
| **NS Credit: Green Spaces** | 2 | The location of green spaces, their areas, and distance from a certain building can be evaluated without any dynamic information sharing. |
| **NS Credit: Natural Resources Conservation and Restoration** | 2 | The metadata of the high priorities areas can be saved and queried in 3D city models without any live connection to the outside world. The impact of planned development on these areas can be assessed by modelling the infrastructure in the 3D city model which does not require real-time data sharing |

[1] This prerequisite does not have any points

| | | |
|---|---|---|
| **TR Credit: Compact, Mixed Use and Transit Oriented Development** | 2 | Compact and Complete Centres (CCC) can be included once along with the transit stops and diverse uses while modelling the 3D city and distance between them can be queried at any time in the static 3D model |
| **TR Credit: Alternative Fuel Vehicles** | 2 | The charging stations for electric vehicles can be modelled once in the 3D city model and their total number can be queried at any given point. The population data can also be stored in the model without any need for real-time updates |
| **TR Credit: High-Priority Site** | 2 | The historic structures, sites, infill sites, and other priority locations can be tagged while developing the 3D city model and viewed later on in the static 3D model. |
| **WE Credit: Stormwater Management** | 2 | Flood risk simulations can be carried out in a static 3D city model. Also, green stormwater infrastructure can be modelled and attributed under vegetation context in a static 3D city model |
| **MR Prerequisite: Waste Performance** | 4 | Information regarding waste created and diverted from landfills, incinerators, etc., can be made obligatory for waste management authorities to be uploaded in the CIM database which can later be queried and viewed, and documented to earn this credit |
| **MR Prerequisite: Special Waste Streams Management** | 1 | Information regarding special waste created and diverted from landfills, incinerators, etc., can be made obligatory for waste management authorities to be uploaded in the CIM database which can later be queried and viewed, and documented to earn this credit |
| **QL Prerequisite: Demographic Assessment** | n/a[1] | The parameters related to demographics such as total residents, number of dwellings, |

[1] This prerequisite does not have any points

| | | |
|---|---|---|
| | | and the location of public offices and services, etc., can be stored in a static 3D city model since this information is not collected in real-time. |
| **QL Prerequisite: Quality of Life Performance** | 6 | The parameters of quality of life such as education, equitability (gross rent, gini coefficient), prosperity (median household income, unemployment rate), etc., can be stored in a static 3D city model since this information is not collected in real-time. |
| **QL Credit: Trend Improvements** | 4 | The parameters such as population with a high school degree, graduation rate, small businesses, unemployment rate, poverty rate, percentage of household incomes, etc., can be stored in a static 3D city model since this information is not collected in real-time. |
| **QL Credit: Distributional Equity** | 4 | The parameters such as median earnings of males and females, high school graduation rate, unemployment rate, etc., can be stored in a static 3D city model since this information is not collected in real-time. Also, the location and distance of parks, recreation areas, libraries, schools, and healthful retail food outlets from any building can be calculated in a static 3D model. |

#### 3.2.1.2. Dynamic 3D city models:

A dynamic 3D city model can be considered as a digitally upgraded version of a static 3D city model with the integration of ICT and IoT into a CIM database or data management platform to establish a real-world connected virtual model (cyber-physical real-time connection). Integration of digital technologies with the CIM database augments the capabilities of a 3D city model and it can be applied to a broad range of applications that require continuous data sharing. The following table shares the LEED parameters which can be fulfilled by a dynamic 3D city model.

**Table 5 – The applications of dynamic 3D city models aligned with LEED parameters**

| LEED Parameter | Possible Points | Applications |
|---|---|---|
| IP Credit: Green Building Policy and Incentives | 4 | The installation of smart meters for energy consumption monitoring and its data collection requires a dynamic 3D city model to receive data through the integration of smart meters, IoT, and CIM data management platform which is desirable for real-time energy data tracking and introducing optimization interventions. |
| NS Credit: Light Pollution Reduction | 1 | Placement of light sensors equipped with data sharing network at required locations to measure Sky Quality and communicate the Sky Quality readings to the CIM model is feasible for monitoring the lighting pollution and take necessary measures if warranted. |
| TR Prerequisite: Transportation Performance | 6 | Smart sensors located at traffic signals connected to the CIM database with an IoT network can record traffic data to perform VMT studies and real-time traffic flow surveys. It can also help to control the signal intervals of traffic lights optimally. |
| TR Credit: Access to Quality Transit | 1 | The number of people using public transportation can be calculated by recording no. of tickets validated, or installing cameras or Infrared (IR) sensors at the bus stops, in the cycling track, footpath, sidewalks, roads, etc. Also, Global Positioning System (GPS) trackers placed in public transport allow receiving real-time location, speed, and direction of the vehicles which is crucial to handle emergencies. A dynamic 3D city model is best suited for fulfilling this credit. |
| TR Credit: Smart Mobility and Transportation Policy | 2 | A dynamic model allows monitoring public transport vehicles that have GPS/GPRS trackers to relay real-time position. Also, for on-ground transit stops, CCTVs and PIS can be visible in a dynamic 3D city information model. RFID and parking space status responses based on IoT can be forwarded to the CIM database by installing embedded sensors at/in parking spots. |

| | | |
|---|---|---|
| WE Prerequisite: Water Access and Quality | n/a[1] | Real-time determination of the level of pollution in potable and wastewater is useful for city authorities to tackle and identify increased pollution promptly, therefore, wireless sensors can be rolled out in the wastewater network to relay data to the CIM database which can be viewed or queried any time and corrective actions can be taken. |
| WE Prerequisite: Water Performance | 6 | Tracking real-time water consumption is accelerated by the installation of smart meters which can be integrated with IoT infrastructure to share and record consumption data in a central CIM database and can be viewed in a 3D dynamic model. |
| WE Credit: Smart Water Systems | 2 | The automation of water supply infrastructure for data collection, tracking, and monitoring equipped with an IoT network makes data accessible and viewable in a dynamic 3D city model in real-time. |
| EN Prerequisite: Power Access, Reliability and Resiliency | n/a | Energy-related data tracking and monitoring are pervasive and popular now with the incorporation of smart technologies such as smart meters and this data is usually stored in BMS and utility company's database. A dynamic 3D model can be provided access and track data in real-time with spatial representation. Any spatial pattern or trend in energy consumption can be identified visually without conducting the cross-referencing of meters' metadata with physical addresses and it can be combined with other parameters such as an increase in water consumption or increase in lighting pollution (due to excessive lighting), etc. to deduce the reason of abnormal energy consumption. |
| EN Prerequisite: Energy and Greenhouse Gas Emissions Performance | 14 | Smart energy meters connected with the CIM database with integrated IoT infrastructure can communicate actual consumption data to the model and it can be compared with the city energy modelling results to identify any abnormalities. |
| EN Credit: Renewable Energy | 6 | The potential of renewable energy, in particular solar energy, can be evaluated in a static 3D city model, however, to monitor the actual supply of energy |

[1] This prerequisite does not have any points

| | | |
|---|---|---|
| | | generated from solar panels, the metering infrastructure can be integrated with the CIM database to feed live energy generation data to a dynamic 3D city model |
| MR Credit: Smart Waste Management Systems | 2 | Underground pneumatic tubes for waste collection can be modelled in a static 3D city model as a utility network, however, smart bin sensors are to be placed in trash bins to disseminate the data to a dynamic 3D model about its fullness status and the nearby garbage trucks can be located with installed GPS/GPRS and notified to empty a full trash bin. |

A dynamic 3D city model is crucial to augment the capabilities of a 3D city model by strengthening the cyber-physical world relationship by utilizing digital means. With the increased popularity of ICT and IoT, a 3D city model holds the potential to incorporate and take maximum advantage of these emerging technologies and aid efficient and responsive city planning, management, operation, and development. Digital technologies can be installed without using a 3D city model and a 3D city model can be developed without incorporating digital technologies, however, it will leave a wide gap in the challenges cities are facing and the solutions required to mitigate them. The unification of digital technologies and 3D city modelling can render spatial context to the digital information and harness amplified benefits induced from the fusion of ICT, IoT, and CIM. It also facilitates investigating multi dimensionalities of parameters in real-time e.g., an increase in energy consumption can be compared against the rise in temperature, increase in water consumption, etc. Therefore, a dynamic 3D city model consolidates the benefits of 3D city models to a large extent.

# 4. SUSTAINABILITY BASED CIM FRAMEWORKS:

## 4.1. Proposed framework for CIM:

Based on a detailed analysis of CIM potential and LEED for Cities & Communities, a taxonomy for 3D city models has been created with the sustainability perspective. As illustrated above, 3D city modelling can be bifurcated into two different modelling approaches based on the data collection process; static 3D city modelling and dynamic 3D city modelling. To conduct a comprehensive LEED assessment, a combination of static 3D city modelling and dynamic 3D city modelling is desired. The assessment limitation of static and dynamic models in LEED perspective based on calculable points is given below in Figure 33.

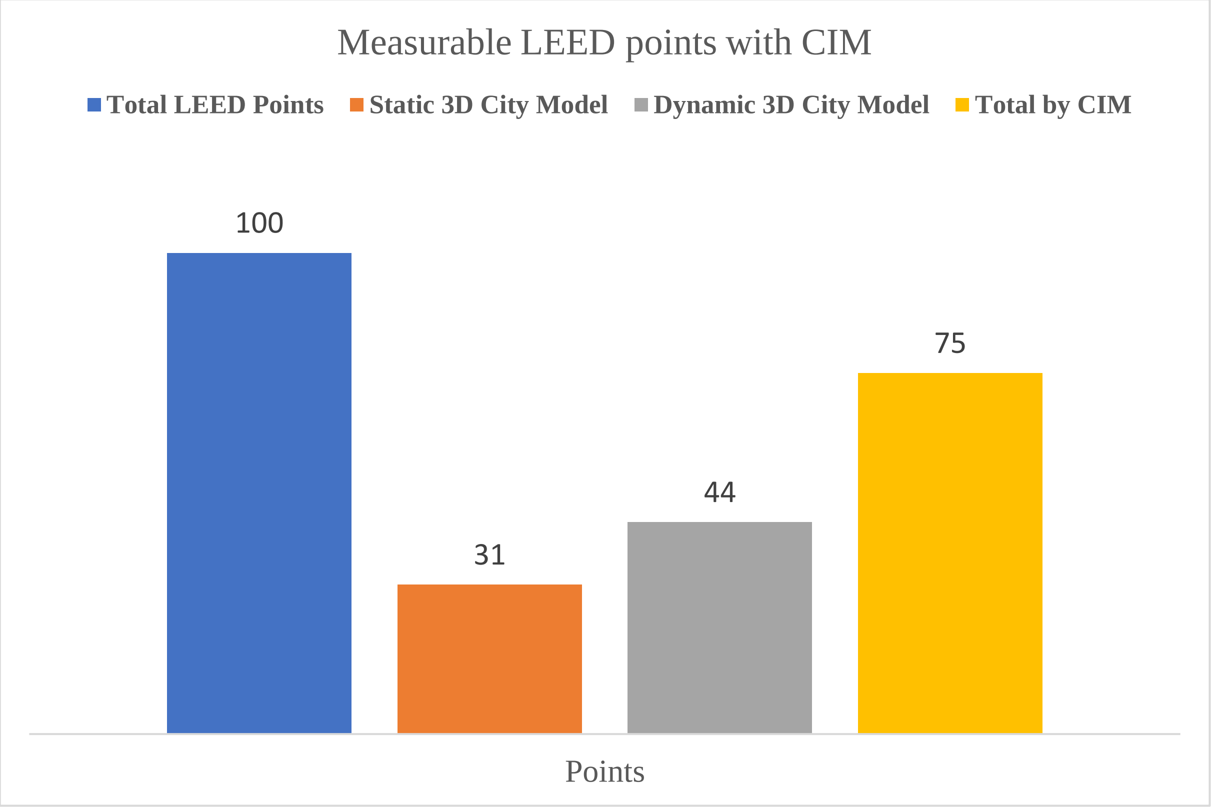


**Figure 33 – LEED points calculability with static and dynamic 3D city models (excluding 10 points of Innovation and Regional Priority)**

It manifests that the data intake capacity and approach of a CIM model play a major role in conducting an extensive estimation of sustainable urban development. Out of 100 points (excluding 10 points of Innovation and Regional Priority categories of LEED), 75 can be evaluated with the implementation of BIM. It implies that the modelling strategy should include the sustainability sphere into account while defining the thematic dimensions in the model. These dimensions must be able to establish and deduce influences on each other and produce feedback to queries made at the user interface since the exploration of sustainable urban development is not a standalone analysis of individual city objects, processes, flows, and society, in fact, it is an integrated approach which seeks to identify interdependence. This interdependence is not possible unless the 3D city model allows city elements to interact with each other, not only for LEED evaluation purposes but as a sustainability computation tool in general. For this purpose, the data collection is divided into modules (layers) as stated in Figure 32. These modules contain the information separately, however, they are interlinked with other modules at the same time and able to impose scenarios on each other and perform the required assessments.

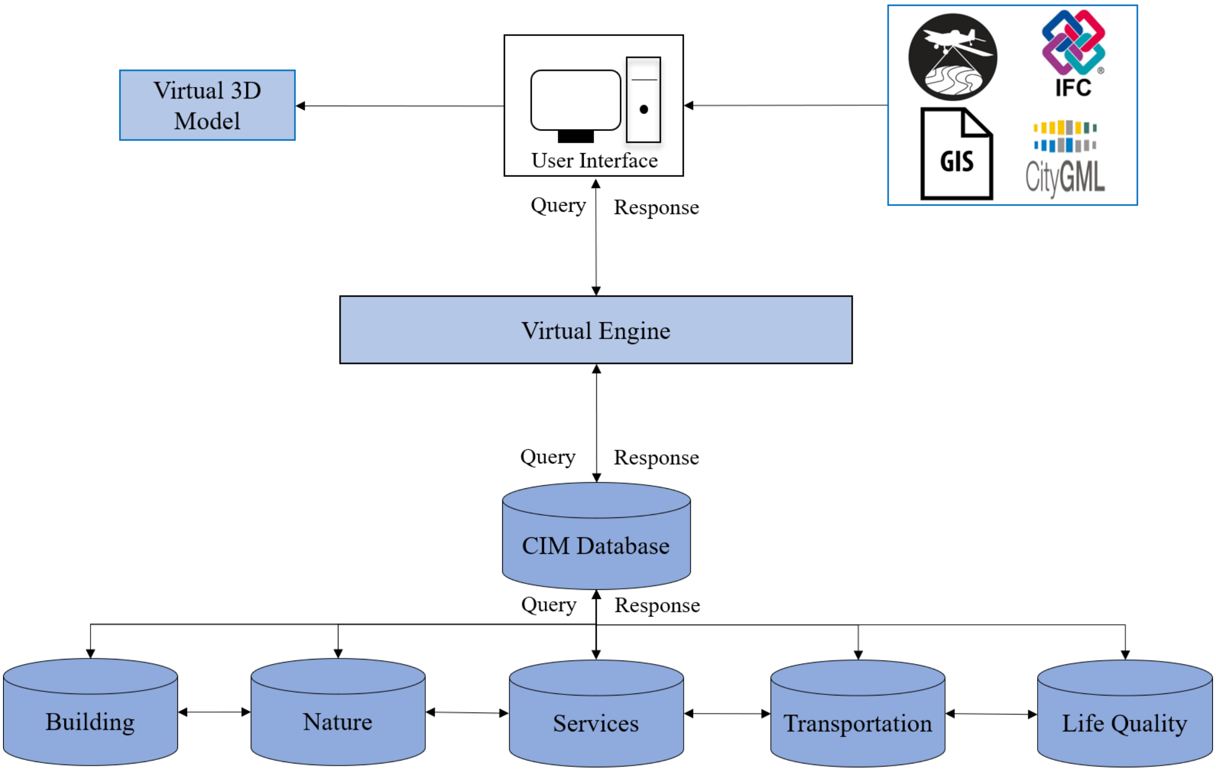


**Figure 34 – Schematic representation of a static 3D city model with separate but interdependent modules**

The above figure manifests the data collection interface, a virtual engine to carry out simulations, analysis, and assessment, and a database with individual modules that are separate but can interact with each other. A 3D city model can be just a graphical representation of cities just like Google Maps, however, to enable quantification of sustainable urban development, the virtual engine is desired to respond to a query made at the user interface by performing an analysis that involves the database and interaction of modules. For instance, for a solar irradiance analysis, the model must be able to identify any trees or barriers that pose shadows on the surface of a house or building or their combination.

However, a static 3D city model does not perceive the real-time mutual interactions of city systems which is indispensable for making evidence-based decisions and timely responses. A dynamic 3D city model incorporated a sensory module in the CIM infrastructure to allow real-time measurements and assessments which are conducted by a virtual engine. In a dynamic 3D city model, a Sensors module is also added to store information regarding the sensors and digital devices and received real-time or near real-time data through IoT. The Sensors module encompasses all other modules where sensors are placed such as smart water and energy meters in a building (a relationship between Sensors module and Building module). The sensors are provided with metadata of the buildings, so they can tender spatial context and representation to the real-time data flow.

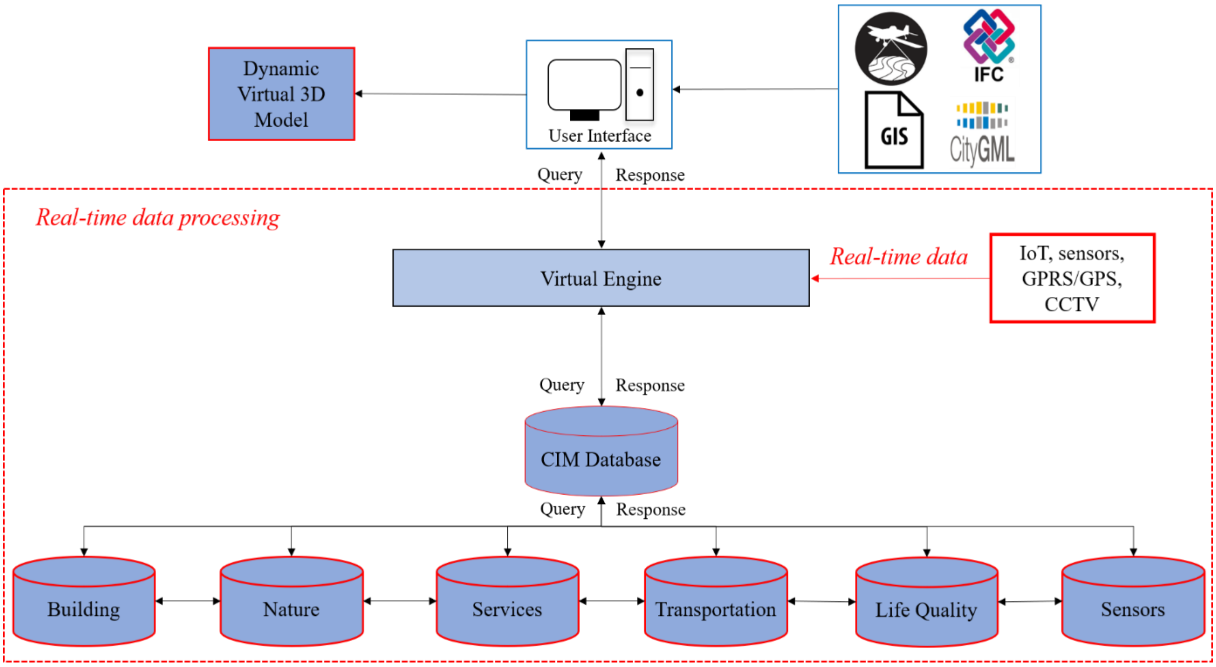


**Figure 35 – Schematic representation of a dynamic 3D city model with sensors module**

At the user interface, the user is enabled to view a dynamic virtual representation of the city with the ability to display only required information by turning all other information off. For instance, a user with an interest in energy consumption wants to visualize or monitor only the energy consumption data, the user interface allows him to disintegrate all the linkage and turn off other modules and information displays and keep smart energy meter function on to have a disaggregated energy consumption information. It will allow displaying the energy consumption data only on the screen. The proposed framework allows using single parameters, multi-parameters, and all parameters to match with the interests of the users. This functionality is very important for a CIM model to embody a unified platform for all city services and service providers.

## 4.2. Proposed framework for Digital Twin development:

The dynamism of a 3D city model should not be confused with the digital twin concept. A dynamic model is the same as a digital twin in terms of real-world conditions' awareness such as environment, traffic, public safety, demographics, level of economic activities, etc., of the city or settlement. However, a dynamic model cannot respond to any change happening in real-time but a digital twin can respond quickly in real-time to changing scenarios and conditions by issuing alarms, notices, warnings, etc., to prevent disasters and dangerous situations and perform other similar functions (*How Digital Twins Enable Intelligent Cities - Huawei Enterprise*, no date). A digital twin is also augmented by artificial intelligence (AI) and big data analytics to predict future scenarios and formulate optimal protocols and contingency plans, unlike a dynamic 3D city model. A digital twin is an up-gradation of CIM with sophisticated technology and functionalities.

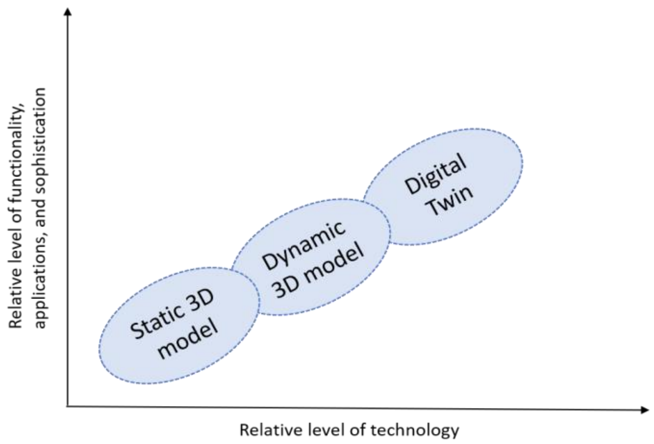


**Figure 36 – Schematic representation of technology incorporation and functionality of static, dynamic 3D city models and digital twin**

A digital twin of a city involves a high level of cutting-edge technologies, a complex amalgamation of digital tools such as IoT and ICT, and actuators to act as decision support tools for city authorities, city planners, designers, architects, actors, stakeholders, etc., to assist in swift and efficient decision-making along with its own ability to respond to various scenarios to predict challenges, issues and devising automated, semi-automated protocols and actions. A framework has been developed for a digital twin development as shown in the picture below:

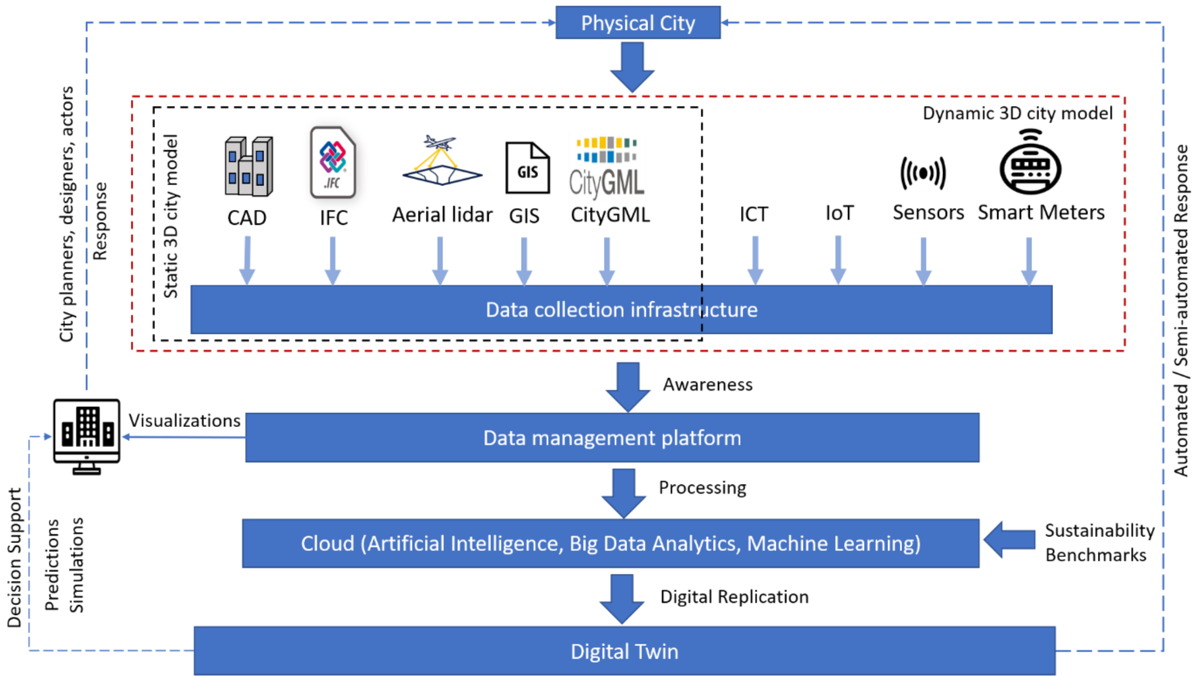


**Figure 37 – Framework for the development of the digital twin**

A static 3D city model establishes the foundation for initiating the incorporation of real-time data flow from digital devices such as sensors, smart meters, GPS/GPRS through IoT and provides spatial context to the data which is an integral part of a dynamic 3D city model. The integration of ICT and IoT with spatial representation enables virtual engine or data management platforms to perform simulations and visualisation.

For a digital twin, the fusion of technologies such as AI, Big Data Analytics, Machine Learning, 5G, etc., is essential for decision support and assessments if the city systems are following sustainability parameters. Sustainability parameters are analyzed by cutting-edge technologies and then cross-referenced with the incoming data from the city systems. The patterns and trends are analyzed, any abnormalities are recorded, optimal responses are suggested, predictions are made, protocols are devised, and automated/semi-automated responses are also conducted accordingly.

A digital twin can be divided into three different layers (1) a physical layer comprised of building module, transportation module, services module, nature module, and life quality module or social module; (2) a digital layer consisted of ICT devices such as sensors, smart meters, GPS/GPRS, etc blended with IoT.; (3) a technology layer which contains cutting-edge technologies to perform different assessments, make predictions, support decision making and provide automated/semi-automated responses.

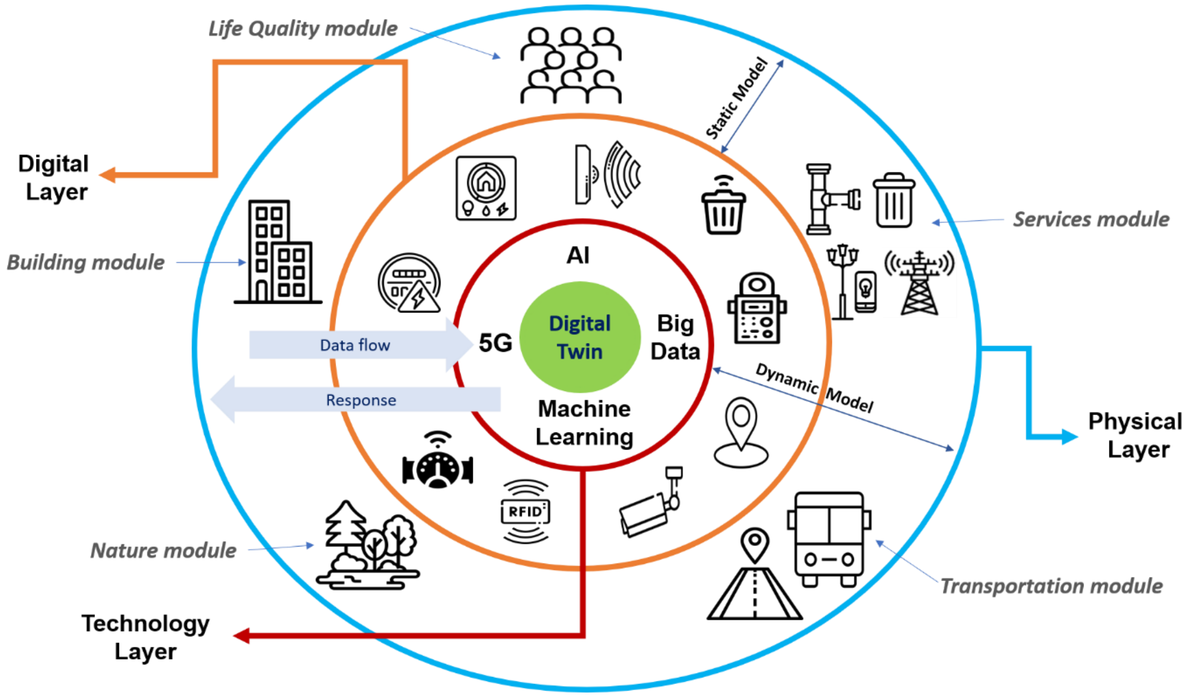


**Figure 38 – Schematic representation of the individual layers of the digital twin**

A digital twin is proposed to be created in different independent layers which are entangled and support each other. A digital twin is innately a combination of different technologies and CIM can provide a spatial context to it. Also, it allows to analyse of the city in three different formats; a static model, a dynamic model, and a responsive digital replication based on the computational power and interests. CIM allows to perform general analysis, simulations, and city performance predictions, however, it is not as capable as a digital twin in undertaking intelligent decisions, reacting to physical world changes, and scenario-based predictive protocols development.

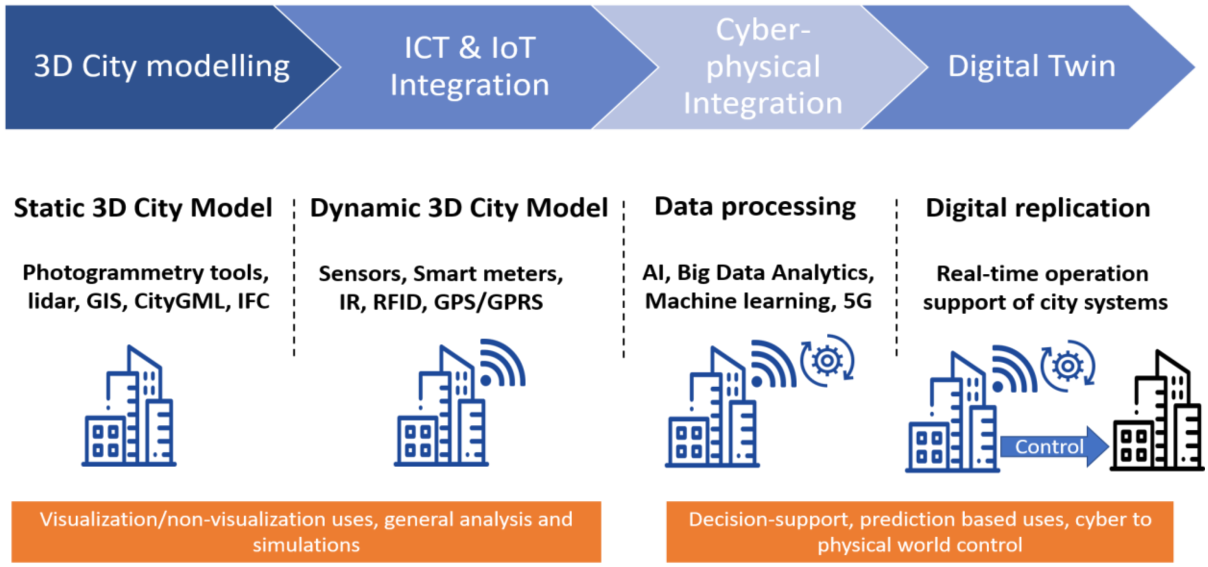


**Figure 39 – City information modelling towards digital twin development**

A digital twin lies at the core of the whole smart city paradigm which receives information, processes it, and responds to an output. A monitoring mechanism like a digital twin is the cornerstone in accelerating the sustainability initiatives, management, and operations of a city. The proposed digital twin's workflow has been developed including sensory readings and their comparison with sustainability parameters stored in the database.

The concept is based on recording benchmarks for sustainable urban development in the CIM database which are consulted continuously for cross-referencing the parameters which are monitored by sensors that supply real-time or near real-time data to the database with wireless technologies. The digital twin stays passive in terms of responses (like a dynamic 3D city model) because it is just monitoring data and not inducing any reaction, however, once the threshold predefined for sustainability parameters is breached, the digital twin becomes active and it notifies the concerned authorities. It also analyzes using AI, Machine Learning, and Big Data if this kind of breach demands human intervention, if yes, then it alerts the concerned department to take immediate action, otherwise, it takes an automated action to rectify the problem. After implementing the solution, it validates the solution by thoroughly analyzing it, by comparing the new readings from sensors to determine if this problem can arise again or is not solved properly. The digital twin may stay passive in terms of reacting to the real-world situation, however, it stays active with regards to analysis, simulations based on predictions and future scenarios, it creates scenarios using its cutting-edge technologies and devises ready-to-implement protocols and solutions. For instance, in case of a fire, the digital twin can analyse how the evacuation plan should be implemented, what are the critical areas, which one is the shortest route, etc., or in case of an epidemic, it can assist decision-makers that what kind of mobility should be desired, it can assess varying social distance requirements, e.g., 2, 3, 4 or 5 meters. It can also identify locations where social distancing would not be possible and devise measures to prevail social distancing. It can also combine scenarios such as a fire in a building and an epidemic. It can formulate evacuation plans while keeping social distancing intact.

There is a network of sensors and meters connected with a digital twin of a city, however, this workflow contains only 3 example smart meters to illustrate the overall description of its working mechanism.

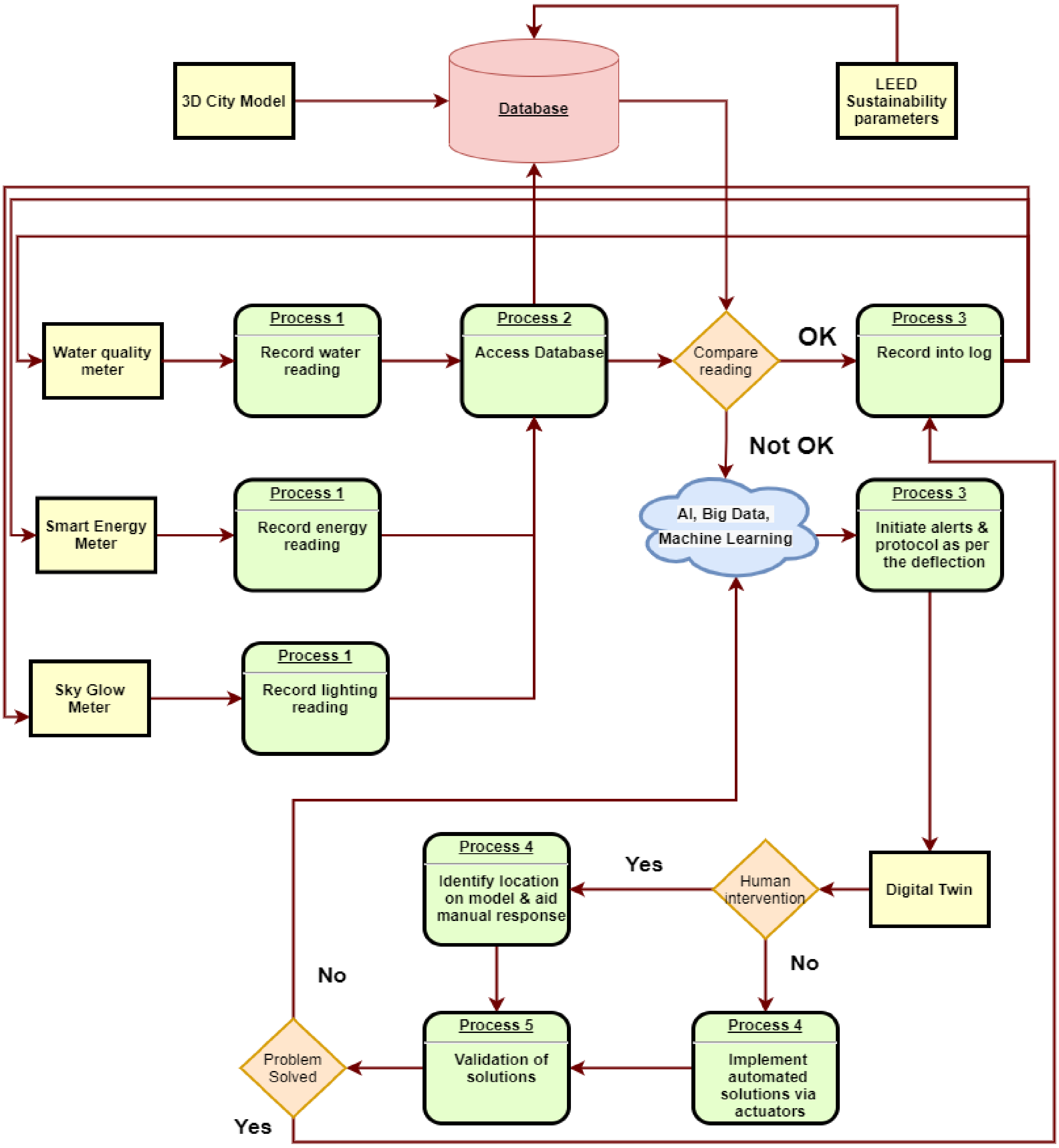


**Figure 40 – Workflow of digital twin based on smart meters and sustainability parameters**

A digital twin is an important aspect of the smart city paradigm which is under extensive attention to make cities sustainable. A digital twin is an amalgamation of high-tech, a state-of-art fusion of digital technologies, systems, and processes. Digital twin encompasses static 3D city modelling, dynamic 3D city modelling (CIM as a whole), and decision support tools, etc. A smart city is an overarching concept which embraces digital twin and its subsets which in turn is a subset of a sustainable city.

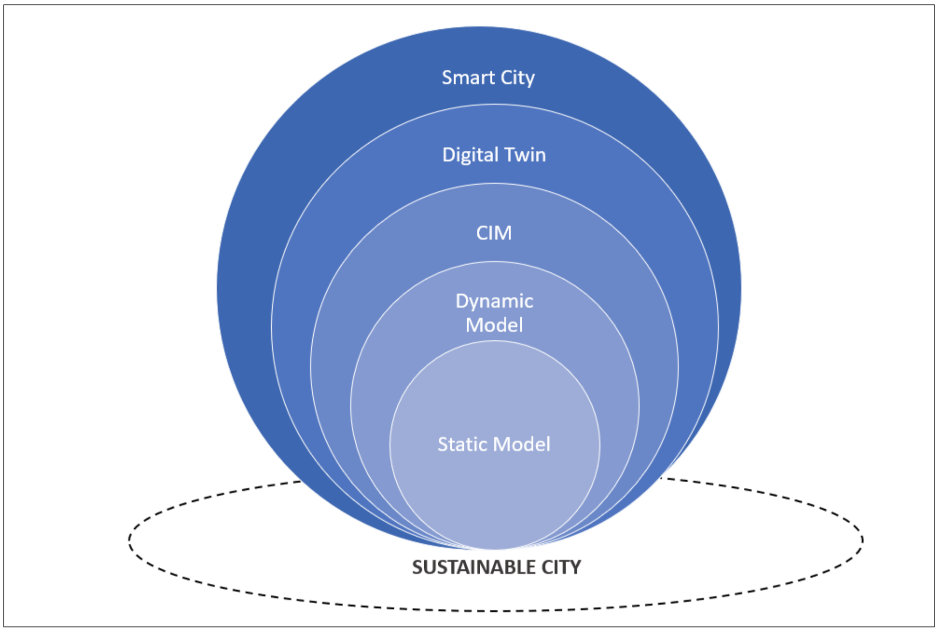


**Figure 41 – Components for developing a sustainable city**

A digital twin enables city planners, administrators, designers, and stakeholders to take decisions that are aligned with the smart city concept and embody sustainable urban development practices. It will transfer the burden from humans to the machine as it is complex to analyze and assess entangled city systems and take effective decisions without relying on cutting edge technologies; the potential of digital twins exhibits promising outcomes in steering the city towards sustainable development.

# 5. CONCLUSIONS

The challenges of cities are continuously increasing with sprawling urban areas, incessant migration of population, and excessive use of resources. The solutions to address city problems are not accelerating at the same rate which is desired to catch up with all the challenges. In fact, a robust city management system is required which is not only ahead of challenges but also analyses the city data comprehensively to predict new challenges that may arise in the future. The sustainable development goals established by the United Nations (UN) offer an approach to target certain areas and monitor sustainable development. The UN's sustainable development goal 11 (SDG 11) focuses particularly on cities that extend a comprehensive approach to pursue sustainable urban development. Furthermore, many organizations such as LEED and BREEAM have also proffered their sustainability benchmarks which match with the SDG 11 of the UN. It mandates that an overarching digital tool should be developed which renders a multidimensional approach to monitor, evaluate, and foster sustainable urban development and serves as an integrated platform for city administrators, managers, designers, planners, actors, businesses, public, etc., to interact and visualize the performance of their cities and devise tailored mechanisms for city operations.

City information modelling (CIM) has been evaluated as a tool in the bid to aid in decision making, planning, and management of cities, however, the full potential of CIM is yet to be discovered. CIM has been employed in a number of applications for cities and many municipalities have recognized its importance. Huge investments have been made in the 3D modelling of cities to develop a platform for virtual experimentation, planning and decision-making, and research and development. It enables city governments to analyse various aspects of their cities, perform prediction-based analysis to be prepared for worst cases, assess the influence of any new development on the neighbourhood, conduct non-intrusive experimentation on a digital platform, etc.

The amalgamation of CIM and sustainable urban development parameters is still in its infancy. The reasons behind it may be due to its large-scale modelling, countless city elements, and systems, a huge amount of data, insufficient ability to distinguish between useful and useless data, high degree of interdependence among the city dimensions, lack of resources, lack of extraordinary computational power, etc. There is also a mismatch in the standardization of 3D city modelling. CityGML, no doubt, has been proffered as an international standard for 3D city modelling data exchange, however, it is still not as pervasive and comprehensive as it ought to be. Yet, the case studies of 3D city modelling manifest that the exploration of the capabilities of CIM is growing which indicates that CIM is emerging and capturing huge interest.

Notwithstanding the growing interest, CIM has not been involved in full-fledge sustainability studies at a city scale or in a conceptual analysis to lay out its applications in a sustainable urban development perspective. To bridge this gap, a detailed assessment of LEED sustainability parameters based on CIM applications has been conducted which unfolds that CIM can essentially be used for estimating and monitoring sustainable urban development in a city. The sustainability parameters of LEED concerns various categories of a city such as buildings, ecology, energy, water, waste management, and society (quality of life). These parameters are evaluated by different methods which involve distinguished data intake requirements. Some parameters warrant one-time data collection (static data) which can be kept until it is changed, i.e., the location of a public park, or a building's access to the water supply. On the other hand, some parameters demand a constant feed of data in real-time or near real-time. For instance, the quality of water, or air quality. Static data does not require a 3D city model to be connected with the physical world in real-time or near real-time which is contrary to the parameters requiring real-time data feed. The collection infrastructure of data bifurcates 3D city models into two categories; static 3D city model and dynamic 3D city model. A static 3D city model can verify sustainability up to a certain extent; however, a dynamic 3D city model augments the capabilities of a 3D city model in general. The developed taxonomy categorizes the uses of 3D city models. Both static and dynamic 3D city models allow measuring 31 and 44 LEED points respectively out of 100 points (excluding 10 points of Innovation and Regional Priority). It manifests that a substantial portion of sustainable urban development can be determined using CIM.

CIM-based sustainable urban assessment implies developing a sustainability-focused framework for 3D city modelling, The proposed framework of the 3D city model separates the model into modules; building module, nature module, services module, transportation module, life quality module, and sensors module. These modules are proposed to be modelled individually, yet in a way that their interaction can be mapped, investigated, and recorded. The emergence of cutting-edge technologies such as Artificial Intelligence (AI), Big Data Analytics, Machine Learning, 5G, etc., enable an inclusive development of a digital replica or a digital twin of a city that allows evidence-based decision-making, predictive protocols, incidents alerts, and automated/semi-automated responses.

However, to realize the concept of the digital twin to its full capacity, certain obstacles have to be overcome such as interoperability issues, latency problems, cybersecurity risks, and physical security risks. The interoperability issues concern the development of 3D models in particular since at the moment there is not such a tool that can perform all evaluations without adding a plugin or sharing the model data with a new tool. This data exchange can cause time waste and information loss. Latency problems arise due to the large number of devices integrated into the same platform and a huge amount of information flowing which can slow down data exchange and responses to certain scenarios which may be addressed using 5G or further advanced technologies. The single inclusive platform also opens a window for hackers with maligned interests to sabotage the integrity of the digital twin and influence the physical city for their vested purposes. This problem can be addressed with the implementation of blockchain and smart contracts and a robust cybersecurity mechanism. Various other physical security challenges may also arise keeping in view the point if emergency services can rely on a 3D city model for their operations, other criminal elements can utilize this platform for their illegal activities. It can be sorted out by rendering limited access to the public to a 3D city model or implementing other data controls. Therefore, before the establishment of an inclusive 3D city model and digital twin, it is essential to devise efficient mechanisms, strategies, and protocols to tackle these hurdles.

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| 3DCM | 3D City Model |
| ADE | Application Domain Extension |
| AI | Artificial Intelligence |
| BIM | Building Information Modelling |
| BMS | Building Management System |
| BREEAM | Building Research Establishment Environmental Assessment Method |
| CAD | Computer Aided Design |
| CCC | Compact and Complete Centre |
| CCTV | Closed-Circuit Television |
| CIM | City Information Modelling |
| CityGML | City Geography Markup Language |
| DB | Database |
| DESA | Department of Economic and Social Affairs |
| DT | Digital Twin |
| EN | Energy |
| GDP | Gross Domestic Product |
| GHG | Greenhouse Gas |
| GIS | Geographic Information System |
| GPRS | General Packet Radio Service |
| GPS | Global Positioning System |
| I | Innovation |
| ICT | Information and Communication Technologies |
| IFC | Industry Foundation Classes |
| IoT | Internet of Things |
| IP | Integrative Process |
| IR | Infrared |
| LEED | Leadership in Energy and Environmental Design |
| LiDAR | Light Detection and Ranging |
| LoD | Level of Detail |
| MR | Materials and Resources |
| NS | Natural Systems |
| OGC | Open Geospatial Consortium |
| PIS | Passenger Information System |
| PV | Photovoltaic |
| QL | Quality of Life |
| RFID | Radio Frequency Identification |
| RP | Regional Priority |
| SDG | Sustainable Development Goal |
| TR | Transportation |
| umi | Urban Modelling Interface |
| UN | United National |

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|---|---|
| VMT | Vehicles Miles Travelled |
| WE | Water Efficiency |