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Green Digital Twin for dynamic sustainability assessment

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STATEMENT OF INTEGRITY

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SOMMARIO

Con la crescente preoccupazione per il cambiamento climatico, il mondo si sta concentrando sul raggiungimento degli obiettivi di sviluppo sostenibile (OSS). Gli SDGs sono l'insieme di obiettivi che influenzano ogni aspetto della vita. Negli sforzi per raggiungere gli SDGs, il Green Deal dell'Unione Europea (UE) è una tabella di marcia per trasformare l'economia dell'UE trasformando i problemi in opportunità. L'ambiente costruito è un settore importante che può accelerare il processo di raggiungimento degli SDG e avere il potenziale per avere un impatto anche su altre industrie. L'adozione del sistema di valutazione della bioedilizia a livello globale si è rivelata un cambiamento di paradigma nel settore delle costruzioni. La domanda di edifici verdi è in aumento e con essa anche le industrie associate si stanno adeguando per soddisfare le esigenze degli edifici verdi. Tipicamente, gli standard per valutare la sostenibilità degli edifici sono stati strutturati in categorie di valutazione, ognuna delle quali include molti criteri e indicatori per ciascun criterio. L'obiettivo di questa ricerca è sviluppare il framework Green Digital Twin da eseguire su tutti i tipi di domini dell'ambiente costruito. Gli obiettivi sono sfruttare i dati BIM, l'IoT e i mezzi digitali per trasformare la checklist statica della sostenibilità in indicatori dinamici (energia, aria, materiale, ecc.) e la verifica delle prestazioni nell'ambiente della realtà virtuale sviluppando Green Digital Twin. I dati del BIM sono stati analizzati in realtà virtuale per condurre la compliance creditizia dei crediti LEED della categoria materiali e risorse. Le EPD dell'elemento di arredo e il contenuto riciclato dell'elemento dell'edificio sono stati verificati nella realtà virtuale. La ricerca ha proposto un quadro completo per la valutazione della sostenibilità in cui sono presenti diversi modelli di gemelli digitali per ciascun KPI (indicatore chiave di prestazione). Il caso di studio effettuato ha convalidato i risultati. Le applicazioni di questa ricerca sono molteplici in quanto ha fornito una metodologia efficace per digitalizzare il processo di verifica del credito, visualizzazione dei dati e monitoraggio in tempo reale dei parametri attraverso il gemello digitale verde. Si è concluso che l'uso della realtà virtuale in combinazione con il gemello digitale può accelerare ulteriormente il processo di certificazione degli edifici ecologici e la rapida conformità del credito dei sistemi di valutazione degli edifici ecologici.

Parole chiave: BIM, Gemello digitale, Sostenibilità, IoT, Realtà virtuale

ABSTRACT

With the increasing concern on climate change, the world is focusing on achieving the Sustainable Development Goals (SDGs). The SDGs are the set of goals that influence every aspect of life. In efforts to achieve the SDGs, the European Union (EU) Green Deal is a roadmap to transform the EU economy by turning the issues into opportunities. The built environment is an important sector that can expedite the process of achieving the SDGs and have the potential to impact other industries as well. The adoption of the green building rating system globally has proved to be a paradigm shift in the construction industry. The demand for green buildings is increasing and with it, the associated industries are also adapting to meet the demands of the green buildings. Typically, standards for evaluating building sustainability have been structured to evaluation categories, each of which includes many criteria and indicators for each criterion. The objective of this research is to develop the Green Digital Twin framework to be executed on all kinds of built environment domains. The aims are to take advantage of the BIM data, IoT, and digital means to change the static checklist of sustainability into dynamic indicators (Energy, air, material, etc), and performance verification in the virtual reality environment by developing Green Digital Twin. The data from the BIM has been analyzed in virtual reality to conduct the credit compliance of LEED credits from the material and resources category. The furniture element's EPDs and recycled content of the building element were verified in the virtual reality. The research proposed a comprehensive framework for the sustainability assessment in which there are several digital twin models for each KPI (key performance indicator). The case study carried out validated the results. The applications of this research are multifaceted as it provided an effective methodology to digitalize the process of credit verification, data visualization, and real-time monitoring of the parameters through the green digital twin. It was concluded that the use of virtual reality in conjunction with digital twin can further expedite the green building certification process and fast credit compliance of green building rating systems.

Keywords: BIM, Digital Twin, Sustainability, IoT, Virtual Reality.

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1. INTRODUCTION

Considering the global impacts of climate change, sustainability is becoming the major concern area for governments, policymakers, industries, and researchers. There is a global consensus that collective efforts are required at all levels to mitigate the negative impacts of climate change. Governments are making policies, researchers are contributing through innovation, and industries are adapting to environment-friendly approaches. Similarly, the construction industry is implementing strategies to reduce its carbon footprint. It is important to mention that the construction sector is one of the major carbon emitters as many industries run in tandem with the construction sector. The concept of sustainable built environment is there to reduce the environmental impacts. The introduction of green building rating systems has standardized the sustainability assessment process. According to the World Green Building Council, “Green building rating and certification systems require an integrated design process to create projects that are environmentally responsible and resource-efficient throughout a building's life-cycle: from siting to design, construction, operation, maintenance, renovation, and demolition”. On the other hand, Building, Information Modelling has transformed the industry and it is useful throughout the project lifecycle. The digital design in construction through BIM has helped a lot in reducing the carbon footprint of the construction industry. However, further innovation is required to optimize the built environment through dynamic sustainability assessment techniques through digital twin technology.

Research studies regarding the sustainable built environment, green buildings rating systems, BIM, and digital twin are significant. The gist of the research studies is that green buildings are an effective way to lower the environmental impacts associated with the construction, BIM has transformed the construction lifecycle and the digital twin domain in the built environment is relatively new. The digital twin studies concluded that like other industries digital twin is immensely useful for the construction sector too. However, establishing the connection of the cyber-physical world and the use of that data is quite complex. The important takeaway from the literature is that the use of IoT, sensors and other data collection methods can provide a huge amount of data of the built environment which can then be used for a whole slew of different purposes. The establishment of Green Digital twin is to take the leverage of the digital twin to assess sustainability. The core objective of this research study is to provide the mechanism for the dynamic sustainability assessment by harnessing the potential of BIM, IoT, AI, and virtual reality. The complex system which will be establishing the connection between the cyber-physical world, collecting data through various IoT, processing the data, getting the output and visualization of those results in the AR/VR environment will be the Green Digital Twin.

This research is based on the case study and also proposed a framework that provides the basis of the green digital twin. The proposed framework is the amalgamation of different digital twin models available. The proposed framework is specific to the built environment but it can be applied to the other domains with some customization. The case study is to check the parameters related to Air and Material from WELL and LEED building standards respectively. Although a large number of parameters can be checked through the Green Digital Twin in this study only two parameters were checked to test the validity of the model.

The thesis has six sections. The literature review was divided into three parts based on the major core areas of the research domain that are sustainability, BIM, and digital twin. The first section of the literature review discusses the concept of sustainability in general then it focuses on the sustainable built environment. This section established the link that why achieving sustainability is important in the construction sector, explains the presence of the green building rating system, and the benefits of the green buildings. The second section is completely dedicated to BIM and its uses in the built environment. This section provides a detailed account of the role of BIM in the construction industry especially from the perspective of the sustainable built environment. In this section, the overview of the BIM tools for sustainability assessment, its applications in the green building certification process, and the need for the Green BIM was provided. The third section is about the digital twin. The digital twin section first defined the term digital twin, its uses in different industries, and what digital twins can do. Furthermore, it explained the evolution of the digital twin from BIM and different models of DTs. The third section of the thesis provides research rationale that why the green digital twin is required, what other studies have shown, and what areas are there that need to be explored. The fourth and fifth sections are about the development of the green digital twin, its basic, defining KPIs, and the proposed framework. The last and sixth section of the thesis is about conclusions based on the case study and how it can be applied for different benefits.

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2. LITERATURE REVIEW

A literature review was conducted to understand the existing research and what is being implemented in the market. The interdisciplinary nature of the project requires a complete understanding of the knowledge and research in different fields. Firstly, sustainable construction, which is a vast topic. However, the scope of this study is limited to the avenues related to green buildings, their rating systems, and their evaluation methodologies. Secondly, the role of Building Information Modelling (BIM) in sustainable construction. Finally, the literature review discusses the digital twin (DT) technologies in detail, their role in green buildings, and facility management.

2.1. Sustainability in Construction and Green Buildings

To explain sustainability in construction it is vital to understand that why it is important to implement or think of sustainability in construction. Researchers and practitioners are concerned about the environmental issues that resulted due to the unprecedented urbanization in the last decade and developments associated with it (Chuai et al., 2021). The construction sector anywhere in the world is one of the most important sectors with a handsome contribution to the global and local economy. According to the studies by McKinsey & Company, the construction sector contributes approximately 14% to the global gross domestic product (GDP) (McKinsey & Company, 2020). According to the estimates, the construction industry is one of the greatest CO₂ emitters accounting for 36% of total greenhouse gas (GHG) emissions and consuming 40% of the global energy (Li et al., 2021.; Wu et al., 2019). Furthermore, The energy consumption in the use phase of the buildings is estimated to be one-quarter of total CO₂ emissions (Huang et al., 2018). Sustainable construction takes inspiration from sustainable development as it aspires to achieve the core values of sustainability.

2.1.1. Definitions and attributes of Sustainability

According to the United Nations Brundtland Commission sustainability is defined as “*meeting the needs of the present without compromising the ability of future generations to meet their own needs*”(United Nations, 2015). There are a lot of other definitions of sustainability and interpretations but the abovementioned is the most widely used one. Sometimes for the business, it is also defined in terms of John Elkington’s coined term of “Triple Bottom-Line”. According to this concept apart from the economic performance, the environmental and social performance must be met to be truly sustainable. The S-E-E model of sustainability reflects that the world is an interconnected system of social, economic, and environmental needs that must be met over time. The global focus on sustainability led to the development of *The 2030 Agenda for Sustainable Development*. At the core of it, there are 17 Sustainable Development Goals (SDGs). These SDGs are a comprehensive set of focus areas that encompass almost all major areas and under SDG 11 (Sustainable Cities and Communities) construction sector is addressed. Therefore, the transition to a sustainable built environment is vital to meet the targets of the sustainable development goals. Continuous improvements over the years have evolved the design, construction, and execution methods, and the body of knowledge is growing in this domain quite rapidly.

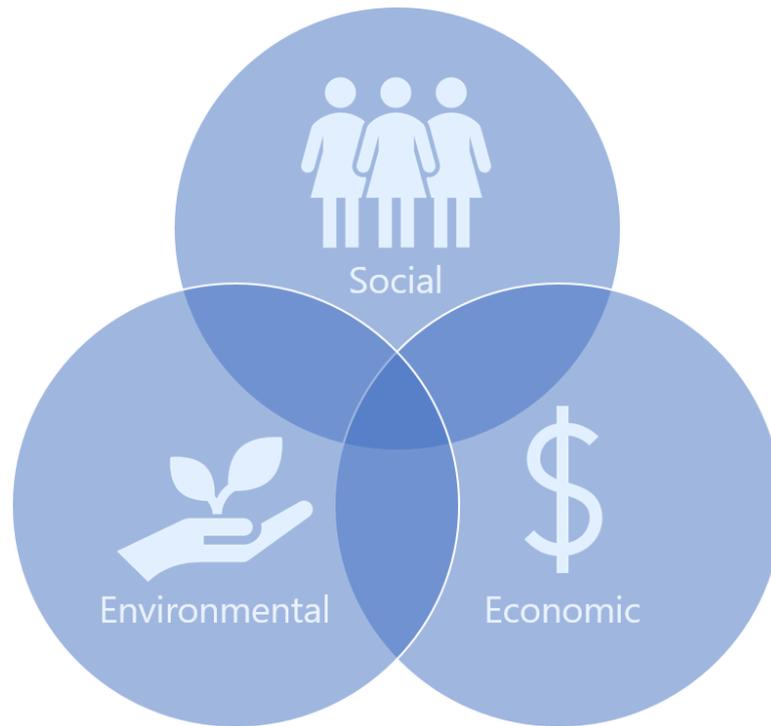


Figure 1 - Sustainability Aspects



Figure 2 - Triple Bottom Line

2.1.2. The sustainable built environment, Green Buildings, and Rating systems

To understand the thought process behind green buildings it is vital to understand the core definition of sustainable construction and the sustainable built environment. There are many definitions and there is no “perfect” definition for that. However, the following are the definitions according to The International Council for Research and Innovation in Building and Construction (CIB);

Sustainable Construction: means manufacture, usage, maintenance, removal, and reuse of buildings and structures or their components in a sustainable manner

Sustainable Built Environment: the contributions by buildings and the built environment to achieving components of sustainable development (CIB, 2021)

Similarly, there is no fixed definition of green buildings definitions and each institute has defined it in its way. However, in the following table, a review of the definitions is provided.

Table 1 - Definitions of Green Buildings in literature

Authors	Green Building Definition
World Green Building Council WGBC (WGBC, 2015)	"A green building is a building that, in its design, construction or operation, reduces or eliminates negative impacts, and can create positive impacts, on our climate and natural environment. Green buildings preserve precious natural resources and improve our quality of life"
U.S. Green Building Council USGBC (USGBC, 2014)	"Green building is a holistic concept that starts with the understanding that the built environment can have profound effects, both positive and negative, on the natural environment, as well as the people who inhabit buildings every day. Green building is an effort to amplify the positive and mitigate the negative of these effects throughout the entire life cycle of a building".
(Y. Li et al., 2014)	"Green construction should be efficient in terms of energy, land, water, and materials, as well as ecologically benign and pollution-free".
(Charles J. Kibert, 2008)	"Green building refers to the design and construction of healthy structures that are resource-efficient and adhere to ecological principles".

2.1.2.1. What makes a Building “Green” and its benefits?

There are different attributes that a building should have to be considered as a ‘Green Building’. According to the World Green Building Council following attributes must be met by a building to be considered as Green Building (WGBC, 2015)

- Improved indoor environment quality
- Efficient use of land, energy, and water resources.
- Incorporation of renewable energy resources
- Responsible use of materials and nontoxic products/materials
- Adoption of circular approach in project and product life cycles.

These are the most common attributes that need to be assessed and verified before considering a building green. The core work of the thesis is centered around the assessment of these attributes and the process is improved further. The benefits of green buildings are proven and various research studies have stated the fact. (Balaban & Puppim de Oliveira, 2017) concluded that the green buildings based on the principles of sustainability are effective in lowering the environmental impacts and ultimately contribute to healthier and clean urban development. Green buildings are considered to improve human health, enhance indoor air quality, water, energy, and be resource-efficient (Chi et al., 2020). Economic benefits associated with green buildings are quite attractive for the stakeholders (Ding et al., 2018). Embodied energy savings and construction waste reduction through material credits in the green building rating systems are immense as pre-approved products essentially use recycle content and help reduce the waste problem (Ding et al., 2018). Apart from the usual energy and water other attributes contributions are also backed by various research studies. The study on green roofs concluded that they play a significant role in reducing the heat island effect and buildings cooling energy demands, particularly in arid regions (Aboelata, 2021). The amount of research on the benefits of green buildings is ubiquitous and almost every region or country has researched the benefits of the research in its way. Furthermore, studies on different parameters and in different regions proved the contribution of green buildings (Azis, 2021; Chang et al., 2015; Y. Chen et al., 2014; Franco et al., 2021; Goussous et al., 2015; Leigh et al., 2004; Shazmin et al., 2017; Sun et al., 2018; To & Chan, 2006; To & Tse, 2003). Due to the initial cost increase in green building projects, it was thought that the green building projects don't justify the cost benefits but later research studies (Ade & Rehm, 2019; Dell’Anna & Bottero, 2021; Dwaikat & Ali, 2018; Fan & Wu, 2020; Gabay et al., 2014; Issa et al., 2010; Khoshbakht et al., 2017; Y. Liu et al., 2014; Meron & Meir, 2017; Ofek & Portnov, 2020) proved that considering the long terms benefit the economic benefits justified and make perfect sense for the economic viability of these projects. In the following picture, various benefits of green buildings are summarised with their impact category.

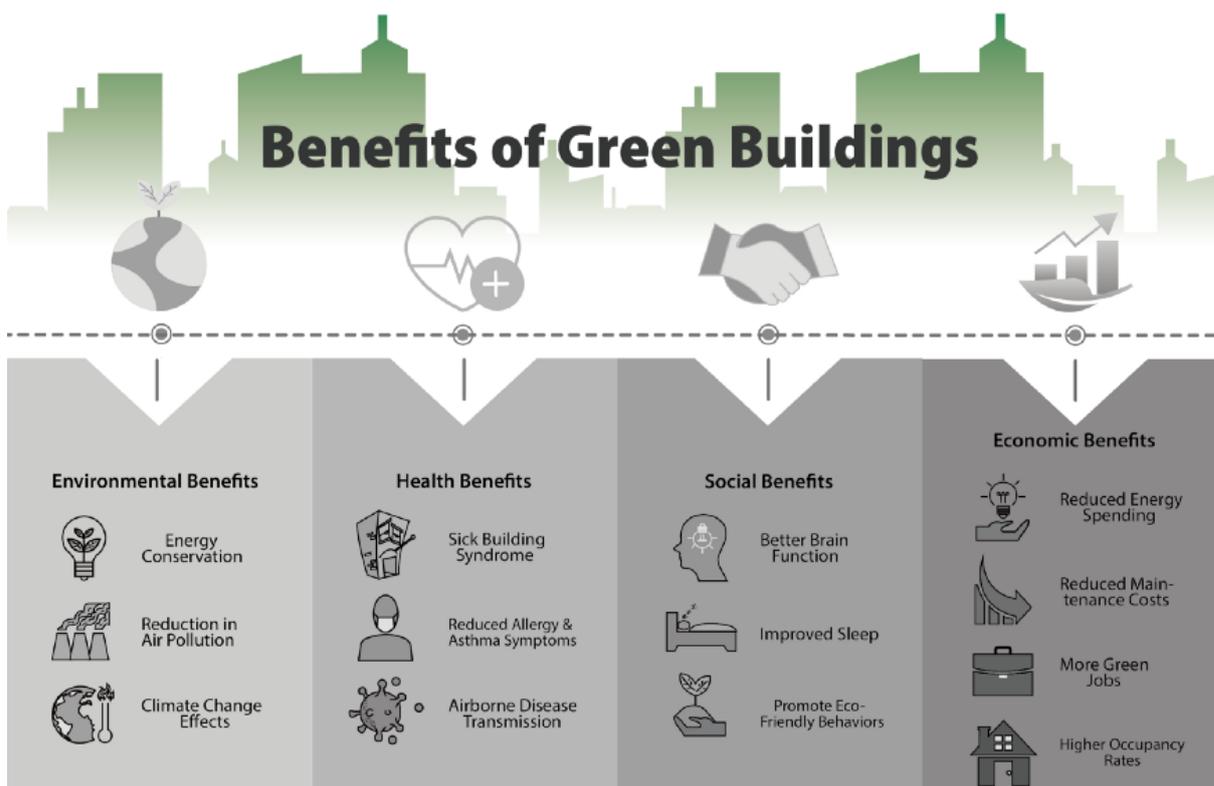


Figure 3 – Benefits of Green Buildings

Although there are various building standards and each building standard have their own set of strategies to implement and issue the rating of the building. Following are the Green Buildings Rating systems that are available over the globe for all kinds of typologies and they are applicable almost everywhere. Although there are many other regional and local standards to be followed here I have just highlighted the most widely used ones or well-known you can say.

These rating systems are the core component of the sustainable built environment domain. All the projects across the globe can get certified with any rating system of their choice. However, LEED, WELL, LFA and BREEAM are widely used across the globe. It is important to understand that the WELL rating system developed by the IWBI is more focused on the health and well-being of the occupants. The focus of other building rating systems on the health and well-being of occupants is limited whereas in the WELL building standard the scope is vast and comprehensive. The scope of this research is inextricably linked with these green building rating systems and attributes.

Table 2 – Common Green Building Rating systems

Green Building Rating System	Country
LEED (Leadership in Energy and Environmental Design) WELL (International WELL Building Institute) Living Building Challenge Green Globes Fitwel	United States of America
Green Star	Australia
BREEAM (Building Research Establishment Environmental Assessment Method)	United Kingdom
DGNB	Germany
Protocollo Itaca and Green Building Council Italia	Italy
BCA Green Mark Scheme	Singapore
Estidama	United Arab Emirates

2.2. Role of BIM in Sustainable Built Environment

Building Information Modelling (BIM) has gained immense popularity in the Architectural, Engineering, and Construction (AEC) industry in the last decade. (Gilkinson et al., 2015) interpreted BIM is an innovative technique and procedure that adds significant value to construction projects throughout every stage of their lifecycle. Many research studies (Azhar, 2011; Ghaffarianhoseini et al., 2017; Succar, 2009; Volk et al., 2014) have highlighted the benefits of BIM in the AEC industry. These studies have provided a comprehensive overview about the use of BIM in the AEC industry and impact in conducting different sustainability assessment. The BIM approach uses a virtual platform to integrate multi-disciplinary geometric and non-geometric project data to enhance the design, execution, and maintenance processes (Redmond et al., 2012). BIM platforms provided a better information exchange mechanism between stakeholders by combining all data flows of the project (Eastman et al., 2011). The collaboration between project stakeholders can improve project planning, visualization, and decision-making (Merschbrock & Munkvold, 2015). In the following picture, the role of BIM has been explained over the different life cycle stages of a project.

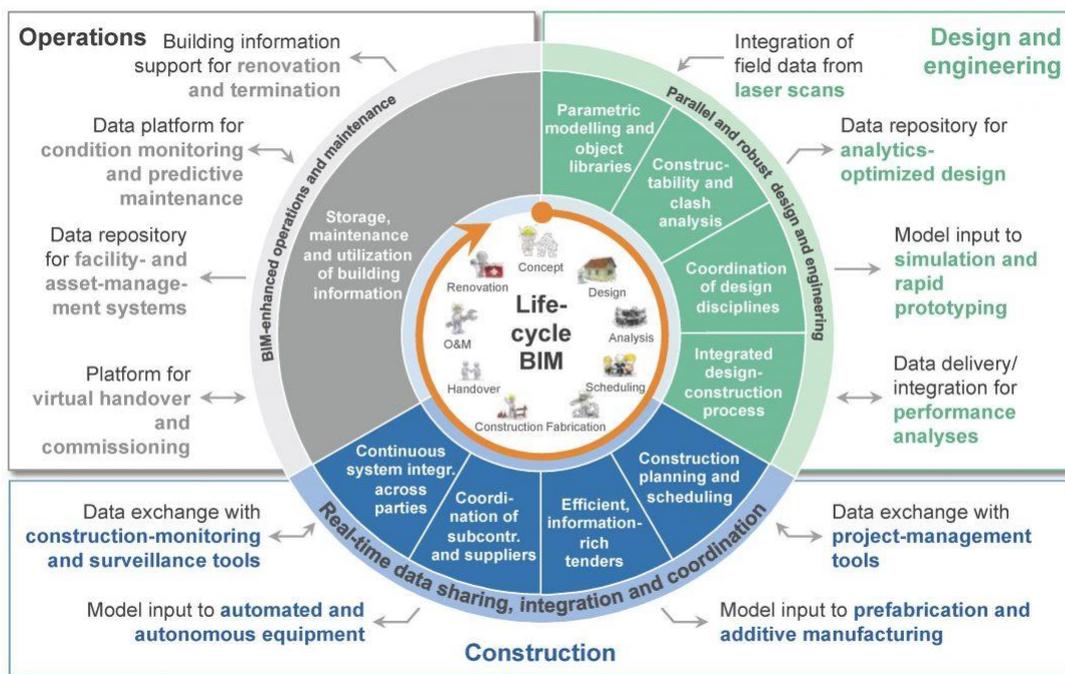


Figure 4 – BIM in the construction life cycle and its application in the AEC industry

2.2.1. BIM and Sustainability Assessment or Green BIM

It is possible to conduct the environmental, social, and economic analysis of the built environment (Schlueter & Thesseling, 2009) in BIM and recent advancements have further improved the efficacy in sustainability assessment of the buildings (Edwards et al., 2019). With the adoption of BIM and supporting tools, the process of assessing the building's sustainability has improved a lot and it has become relatively precise and less hectic (Carvalho et al., 2020). The sustainability assessment of the building is highly dependent on the quality of the data and the phase of the design stages (Azhar & Sattineni, 2010; Basbagill et al., 2013a). According to (Santos et al., 2019), it is preferable to conduct sustainability evaluations at the preliminary design stages to weigh different design options and their impact. To have a complete sustainability assessment a lot of multidisciplinary data must be analyzed with different methods and procedures and BIM tools are quite helpful in optimizing the process. Sometimes these software packages or platforms work within the BIM tools or use the input data from the BIM platforms (Carvalho et al., 2020). BIM adoption in the sustainability assessment is not uniform over the world and only the project teams with good BIM implementations can take advantage of BIM tools for sustainability assessment (Olawumi & Chan, 2018). A considerable number of research studies are available in which different workflows and mechanisms have been explained for BIM adoption in sustainability assessment. The following framework was proposed by the researchers in a case study to streamline the BIM-based process of optimization and evaluation.

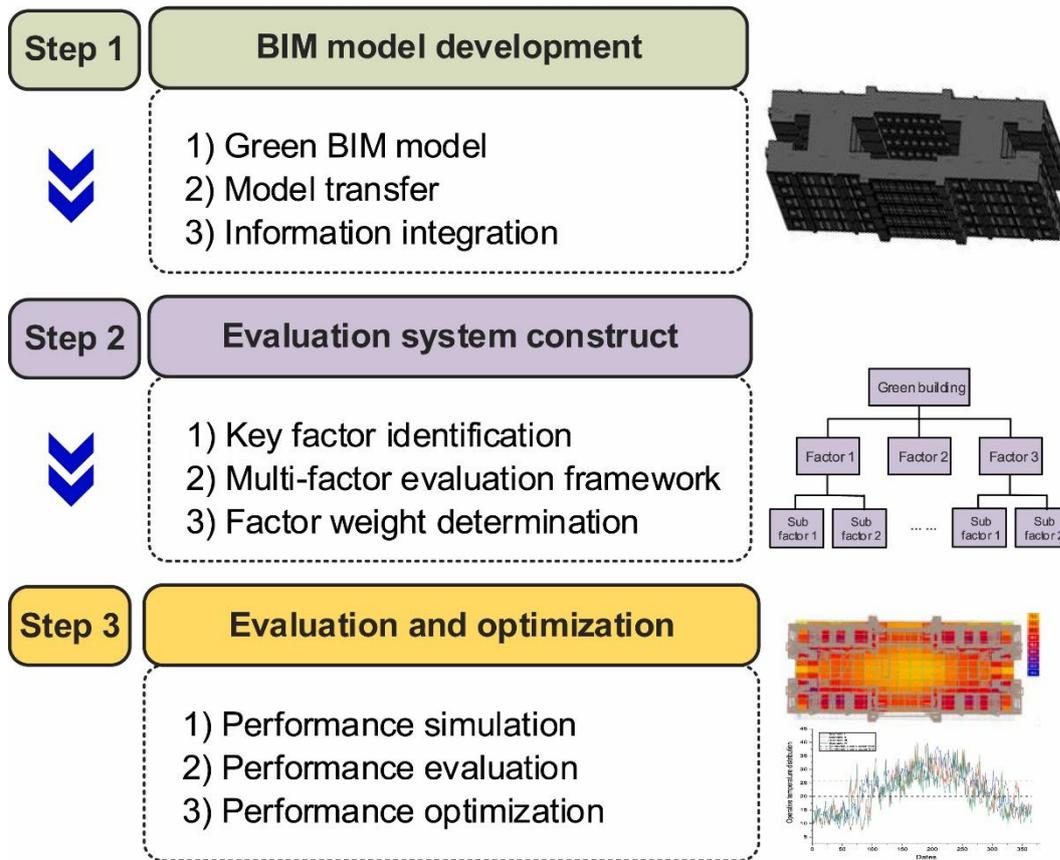


Figure 5 - BIM-based green building evaluation and optimization (Guo et al., 2021)

Information regarding the diverse categories of buildings can be added to the virtual model. Moreover, this information can be used later for various sustainability assessments and project management purposed through standalone software, plugins, or cloud-based platforms (Pan & Zhang, 2021). Appropriate tools can catalyze the process of green buildings certifications by offering precise evaluations, overcoming interoperability issues, and better integration with design authoring software (Pan & Zhang, 2020). (Akinade et al., 2015) proposed a BIM-based approach to facilitate the responsible use of materials and reduce waste by measuring the potential of de-constructability of buildings. Moreover, (Ghaffarianhoseini et al., 2017) concluded that BIM improved the design process, and using BIM was beneficial in obtaining the Green Star rating for the buildings. The benefits of BIM are not just limited to the design and sustainability assessment but it can be used for facility management and retrofitting interventions (Khaddaj & Srour, 2016). In the following table, an overview of various studies regarding BIM and sustainability practices is provided

Table 3 – BIM application and uses in AEC industry

BIM adoption for sustainability Assessment	Reference
Reduce environmental impacts in the project life cycle	(Ajayi et al., 2016)
Waste reduction through design for dis-assembly	(Akinade et al., 2017)

Life-Cycle Analysis (LCA) for sustainability assessment	(Lundin & Morrison, 2002; Soust-Verdaguer et al., 2017)
Embodied energy evaluations and sustainable design	(Bynum et al., 2013; Shadram et al., 2016)
Early-stage design evaluation of design iterations	(Alsayyar et al., 2015)
Better code compliance in project delivery	(Olawumi & Chan, 2018)
Daylighting simulations and analysis	(Kota et al., 2014)
Predictive energy analysis and performance simulations	(S. Lee et al., 2015)
Innovation and new construction methods capability	(Akintoye et al., 2012)
Resource planning and sharing information	(Akintoye et al., 2012)
Building energy consumption simulations and performance evaluation	(Abanda & Byers, 2016; Chandel et al., 2016; de Boeck et al., 2015; Habibi, 2017; Kuo et al., 2016)
Economic benefits with improved cost performance	(Bynum et al., 2013)
Environmental sensitivity analysis and accuracy of building information geometric and non-geometric data	(Abolghasemzadeh, 2013)
Social, environmental and economic evaluation of the buildings	(Antón et al., 2014)
Knowledge integration, multidisciplinary data sharing (Project Management, Safety, Earned Value Analysis, etc)	(Anim–Wiredu & Nani, 2021; Y. Lu et al., 2021)

Sustainability analyses of buildings are of various needs and highly dependent on the scope of the study. Some projects and studies are specific to building rating systems and the core component of every evaluation is to produce the results to get the certification for the project. Many software and tools are available that are being used to get the results. Considering the nature of the green building rating systems and availability of the BIM tools the following table is a summary of the Green Buildings Credits achieved by using the BIM platforms and tools.

Table 4 - BIM software and platforms used for sustainability assessment

Software Used	Credits Achieved	Rating System/ Typology	Reference
Revit, Green Building Studio	IEQ	LEED New Construction	(Zainudin et al., 2016)
Energy Plus, IES-VE EDSL TAS	EA	LEED New Construction	(Schwartz & Raslan, 2013)
ArchiWIZARD, Excel, PEREN, Revit	SS, IEQ, EA	LEED Core and Shell	(Salgueiro & Ferries, 2015)
ArchiCAD, Revit, SimaPro, ATHENA	MR, EQ, IEQ	LEED New Construction	(Basbagill et al., 2013b)
Revit, Tally	MR, IEQ, EQ	LEED All typologies	(Najjar et al., 2017)
Revit, Dynamo	Pilot Credit SS	LEED Core and Shell	(Sanhudo & Martins, 2018)
STAAD PRO, eQUEST, Revit	MR, EA	LEED Schools	(AbouHamad & Abu-Hamd, 2019)
Revit, Athena Impact Estimator (AEI), Excel	EA, IEQ, SS, MR	LEED New Construction	(Jrade & Jalaei, 2013)
Revit, IES-VE	IEQ, MR, EA	LEED New Construction	(Azhar, 2011)
Eco-Scorecard, Revit, Ecotect, IES-VE, AEI	EA, MR, EQ	LEED New Construction	(Farzad Jalaei & Ahmad Jrade, 2014)

Revit, Genetic Algorithms, Simulation Tools	MR	LEED New Construction	(Marzouk et al., 2018)
Dynamo, web service API	LT	LEED New Construction	(J. Li et al., 2019)
Revit, eQUEST, Design Builder	EA	LEED New Construction	(Ryu & Park, 2016)
Revit, Mapping Apps	MR, LT, SS	LEED New Construction	(P. H. Chen & Nguyen, 2017)
Design-Builder, Ecotect, Energy Simulator, IES-VE, AECOsim	Energy, Health and WELL Being, Material	BREEAM UK Fit-out	(Edwards et al., 2019)
ArchiCAD, Visual Studio, Revit, Visual Basic	Energy, Material, Health and WELL Being, Waste,	BREEAM Commercial and Offices	(Ilhan & Yaman, 2016; Oti et al., 2016)

Water Efficiency = WE, Energy and Atmosphere =EA, Materials and Resources = MR

Location and Transportation = LT Indoor Environment Quality = IEQ Sustainable Sites = SS,

2.2.2. Key Findings of BIM adoption for Sustainability Assessment

After a comprehensive literature review from the perspective of overall BIM adoption in construction in general and in following are the key takeaways of the review

- Academic studies are mainly investigating design optimization and embodied energy. Green buildings Standards or rating systems are largely focusing on the aspects related to land use, material resources, energy performance, air, water, and indoor environmental quality (Chong et al., 2017).
- The complete potential of BIM is yet to be explored by the AEC industry in sustainability assessment. “Green BIM” is still in its infancy. Life cycle and energy analysis are the most

common analysis types done on BIM platforms and tools either at the conceptual and detailed design stage (Wong & Zhou, 2015)

- Integration of LCA tools with BIM proved to be successful to quantify the environmental impact assessments and evaluating different design options for all kinds of typologies. Moreover, the majority of the LCA case studies are primarily for the materials credits but synergies can also be developed for the energy credits (Soust-Verdaguer et al., 2017)
- The number of research publications in the sustainable built environment domain are getting higher because of the interdisciplinary nature of the research. However, the research studies focusing simultaneously on three dimensions of sustainability are quite less (Santos et al., 2019).
- Location, density, connectivity, and transportation credits are rarely addressed in the literature but some researchers have addressed them as well. LEED is the most discussed and researched building standard. Extensive assessment of Energy, material, and indoor environmental quality has been done through Revit and application programming interface (Ansah et al., 2019).
- Simplified, linear, and empirical workflows and frameworks have evolved to more comprehensive assessment methods for environmental impact and structural resilience (Díaz-López et al., 2019).
- Green BIM improvements will further expedite the green building assessment accuracy and quality. BIM will remain the essential component for the design, coordination, execution, planning, customized analysis operations, and maintenance (Y. Lu et al., 2017)

2.3. Digital Twin and Sustainable Built Environment.

As discussed in the previous chapter that BIM adoption has transformed the built environment life cycle in many ways for all the stakeholders. On the other hand, technological innovation especially the Internet of things (IoT) implementation in different industries has provided better insights into the systems and enhanced data quality for decision making. Construction projects are data-intensive and the whole life cycle of any project is dependent on data input from various sources and stakeholders. The influence of tech-based solutions is ubiquitous in different industries. Digital transformations provided new avenues to enhance the economic, social, and environmental resilience of systems. Similarly, the integration of sensors, IoT, cloud computing, Artificial Intelligence (AI), and other supporting technologies that are reshaping the construction industry have led to the emergence of Digital Twin (DT) in construction (Lu et al., 2020). Although the concept of the digital twin is new and yet in nascent stages for the construction industry (Lu et al., 2019). However, other industries especially the manufacturing sector is using this quite efficiently for the last two decades.

2.3.1. Definition of Digital Twin

The concept of the Digital twin has evolved over the years and many definitions are there to explain it. Academia and industry have defined the terms differently. Therefore, it is important to have a look at

the different definitions of DT. In the following table, some of the popular definitions of a digital twin have been highlighted to provide a perspective regarding the digital twin.

Table 5 – Definition of Digital Twin

Definitions of Digital Twin	Reference
“It is referred to as digital shadow, digital replica or digital mirror - is a digital representation of a physical asset. Linked to each other, the physical and digital twins regularly exchange data throughout the PBOD lifecycle and use phase. Technology like AI, machine learning, sensors, and IoT allows for dynamic data gathering and right-time data exchange to take place”	(buildingSMART, 2020)
“A digital twin is an exact digital replica of a physical asset—an up-to-date thread of information for every component of a project. It brings together design, construction, and operational data to improve efficiencies and help reduce the total cost of ownership for your customers”	(Autodesk, 2021)
“Is a virtual mirror, which can describe the comprehensive physical and functional properties of the product throughout its life cycle and can deliver and receive product information”	(Tharma et al., 2018)
“DT mainly contains real-time data acquisition technology, data mapping technology, and data-based prediction technology can make the convergence between the physical product and virtual space a reality”	(J. Liu et al., 2019)
“DT is a replica of a physical asset, process or system used for control and decision making”	(Vatn, 2018)
“DT describes the vision of a two-way relationship between a physical artifact and the set of its virtual models.”	(Schleich et al., 2017)
“A digital twin represents a coupled model of the real machine that operates in the cloud platform and simulates the health condition with an integrated knowledge from both data-driven analytical algorithms and other available physical knowledge”.	(J. Lee et al., 2013)
“A digital twin is a virtual representation of an object or system that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning, and reasoning to help decision-making.”	(IBM, 2020)
“Digital twin is an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical	NASA

models, sensor updates, fleet history, etc., to mirror the life of its flying twin”.	
“A digital entity that reflects physical entity’s behavior rule and keeps updating through the whole lifecycle”	(M. Liu et al., 2021)
“Digital twin is a connected and synchronized digital replica of physical assets which represent both the elements and the dynamics of how systems and devices operate within their environment and live throughout their lifecycle”.	(Borth et al., 2019)
“Multi-domain and ultrahigh fidelity digital model integrating different subjects such as mechanical, electrical, hydraulic, and control subjects”.	(Luo et al., 2018)
“One-to-one virtual replica of a “technical asset” (e.g., machine, component, and part of the environment)”.	(Schluse et al., 2018)
“A Digital Twin is an integrated simulation of an as-built system that mirrors its real-life counterpart by using models, sensors, other smart devices”.	(Glaessgen & Stargel, 2012)
“Digital twins represent very realistic models of the current state of the process and their behaviors in interaction with their environments in their real world”.	(Rosen et al., 2015a, 2015b)
“Digital twin can be regarded as a paradigm by means of which selected online measurements are dynamically assimilated into the simulation world, with the running simulation model guiding the real world adaptively in reverse”.	(P. Wang et al., 2019)

2.3.2. Evolution of Digital twin from BIM

The concept of the digital twin was first introduced by Michael Grieves. He presented that it is the digital equivalent of the physical product (Shannon Flumerfelt et al., 2019). Later on, Many industries have adopted the concept of the digital twin but it emerged from the aerospace industry. The figure below is the concise explanation of Grieves’s concept of the digital twin, which was the starting point of modern and complex DTs (Michael Grieves, 2014).

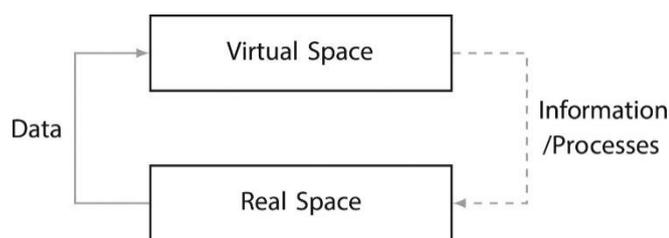


Figure 6 – Initial simplified Digital Twin conceptual framework

The building industry has adopted this concept with advancements in BIM and methods that improved the information or data exchange between different platforms. It has already been explained in the above chapters that BIM has steadily changed the way built environment information is created, sorted, and exchanged through different tools and platforms (Kubicki et al., 2019). The presence of Industry Foundation Classes (IFC) and its wide adoption in the industry has further facilitated the process of information exchange (Bradley et al., 2016). Apart from the design authoring tools, the capabilities of BIM improved and it expanded to complex energy and lifecycle analysis across the built environment domain. In the following picture percentage of research studies conducted on different BIM uses has been shown which depicts that the industry is relying largely on BIM tools for effective project delivery

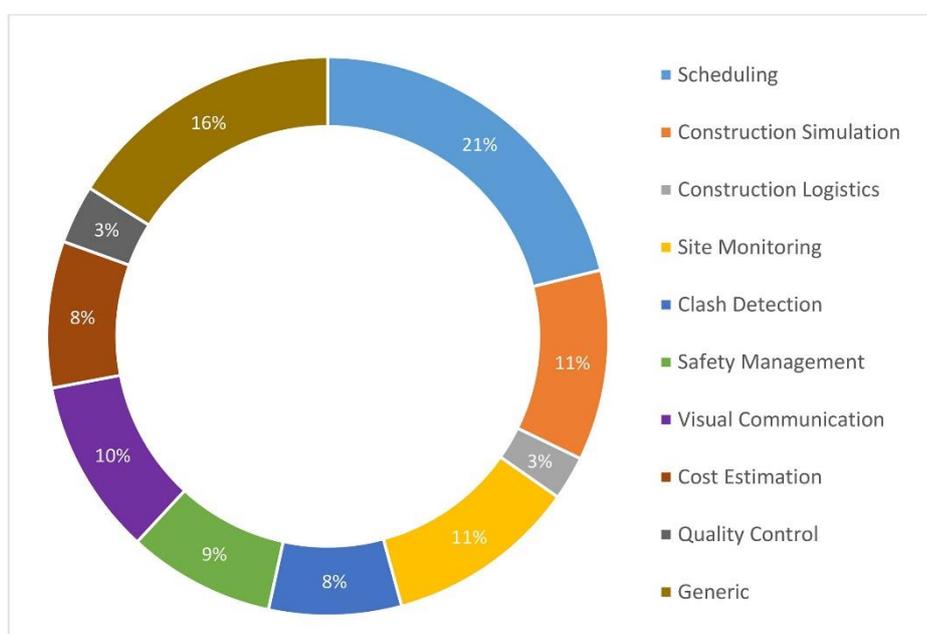


Figure 7 – Distribution of studies on BIM uses in Construction

Conversely, BIM is being confronted with substantial issues, with big data, IoT, and AI being considered as viable solutions for the whole lifecycle of the built environment. BIM platforms and tools are quite efficient in terms of interoperability and the transition from ISO STEP to IFC proved to be effective (Pauwels et al., 2017). However, the concept of the smart built environment and more complex data-intensive processes created the need for the inclusion of AI, IoT, and data analytic for better-built environment design and operations (Shaun Howell & Yacine Rezgui, 2018). The dimensions of BIM depict the new level or layer of information that has been added. For example, the 4D modeling of BIM

explains the time dimension in the BIM environment and all aspects of the BIM model can be analyzed with the perspective of time. The introduction of nD BIM has replaced the word of dimension with application domains, further widening the horizon of BIM (Charef et al., 2018). Furthermore, with the addition of lean construction (Guerrero et al., 2017), health and safety (Shang & Shen, 2016), environmental aspects (engineering & 2017, n.d.), and site monitoring (Kim et al., 2013) the complexity of the nD BIM increased. A review study studied the evolution of BIM to digital twin by defining the levels of the BIM and the functionalities associated with them and then ultimately leading to the digital twin (Deng et al., 2021). The definitions of BIM levels as per the study are as follows:

- Level 1 – BIM- Building Data Geometric and Non-Geometric,
- Level 2 – BIM-based simulations,
- Level 3 – BIM integrated with sensory data and IoT,
- Level 4 – BIM with AI techniques
- Level 5 – Digital Twins.

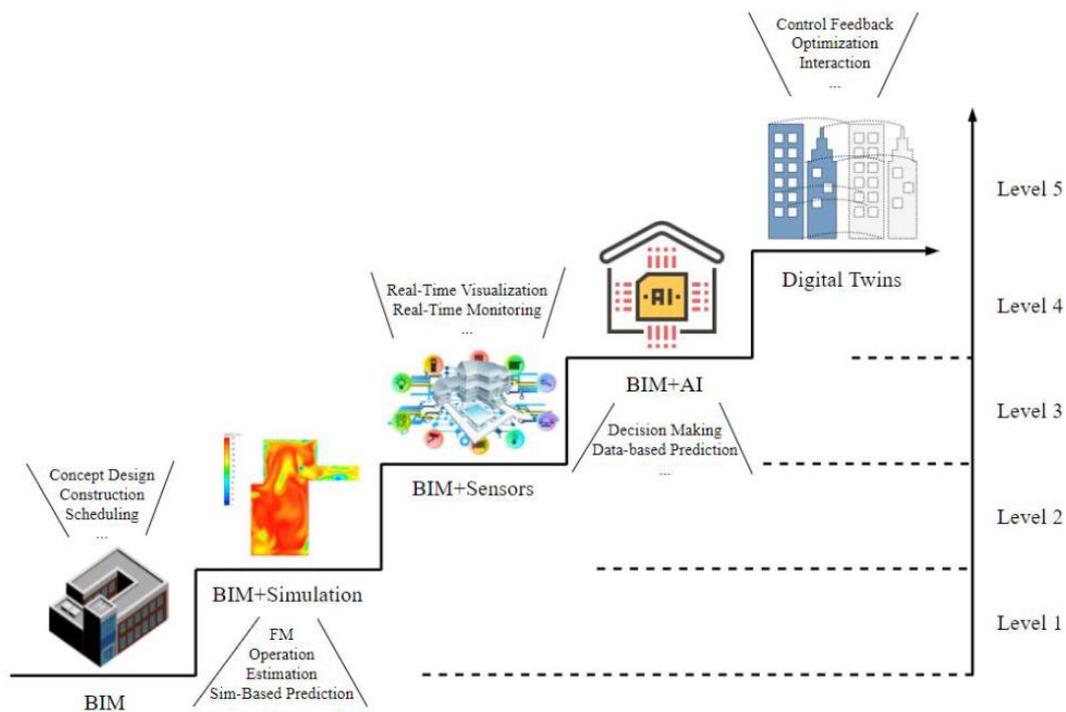


Figure 8 – BIM evolution to digital twin (BIM levels, functionalities, and evolution to digital twin)

Considering the different dimensions of BIM and data-intensive processes throughout the built environment lifecycle the concept of the digital twin evolved from BIM to enhance BIM functionality. In comparison to the BIM, the levels for the DTs standards are not yet matured. The level of development (LOD) as proposed by the American Institute of Architects (AIA) and further refined by the BIM Forum are quite well defined. They use as a standard in the BIM domain. The LODs enable

BIM professionals and other stakeholders to describes the features of model elements from various building systems at various stages of development. The LOD for BIM is as follows

Table 6 - BIM LOD and their characteristics

LOD	Design Stage	Characteristics
LOD100	Conceptual design	Generic representation with only basic representation of elements is there. Only abstract or raw information at this stage is available.
LOD200	Basic design	Approximate information will be at this stage. A generic system, object, or assembly with approximate quantities, size, form, location, and orientation is graphically represented as a Model Element within the Model.
LOD300	Detailed design	Refers to the modeling of elements with exact dimensions, forms, positions, and numbers. The project origin has been determined, and the element has been precisely positioned to the project origin.
LOD400	Fabrication and assembly	Covers production, assembly, and installation information
LOD500	As-built	At this stage dimensions, forms, positions, orientations, and amounts of model elements are compared to constructed elements

In contrast to BIM, the accuracy, information exchange, data transfer and level of abstraction from the model is not that mature or defined in the digital twin domain. As the digital twin models inherit a lot of data that's why researchers (Davila Delgado & Oyedele, 2021) suggested that there must be standards similar to the BIM LODs to meet the requirements of the built environment domain. The major difference between BIM and the digital twin is due to the problems related to the asset instrumentation and data synchronization between physical and digital assets. The prime focus of DTs is on the operations side while BIM is useful in replicating the information of the physical assets. This data repository is the linkage between BIM and the digital twin, where the digital twin works on the data inputs from the BIM models. In the following picture, the division and functionalities of the BIM and digital twin are shown by the researchers (Davila Delgado & Oyedele, 2021).

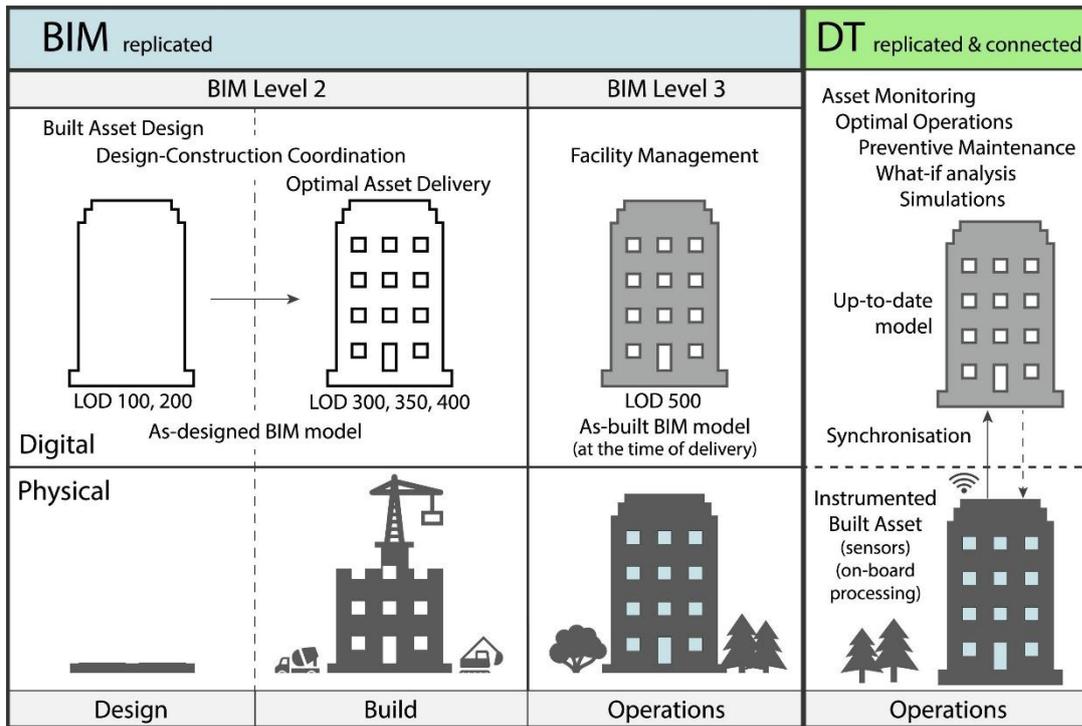


Figure 9 – Generic difference between BIM and digital twin

2.3.3. Digital Twin frameworks and Built Environment

The use of digital twins in a built environment is inextricably linked with the BIM adoption as only the BIM is considered as the foundational block of the digital twin. Irrespective of the industry domain “Data” is the key to the development of the digital twin. Different research studies have explored the potential of the digital twin in the built environment and presented a diverse set of digital twin models. According to the Ernst&Young (EY) white paper, digital twins have four major applications within the built environment. The four applications are (i) Building maintenance and operations (ii) Health and wellness (iii) Enhanced occupant's experience and data collection for decision making (iv) Sustainability evaluation.

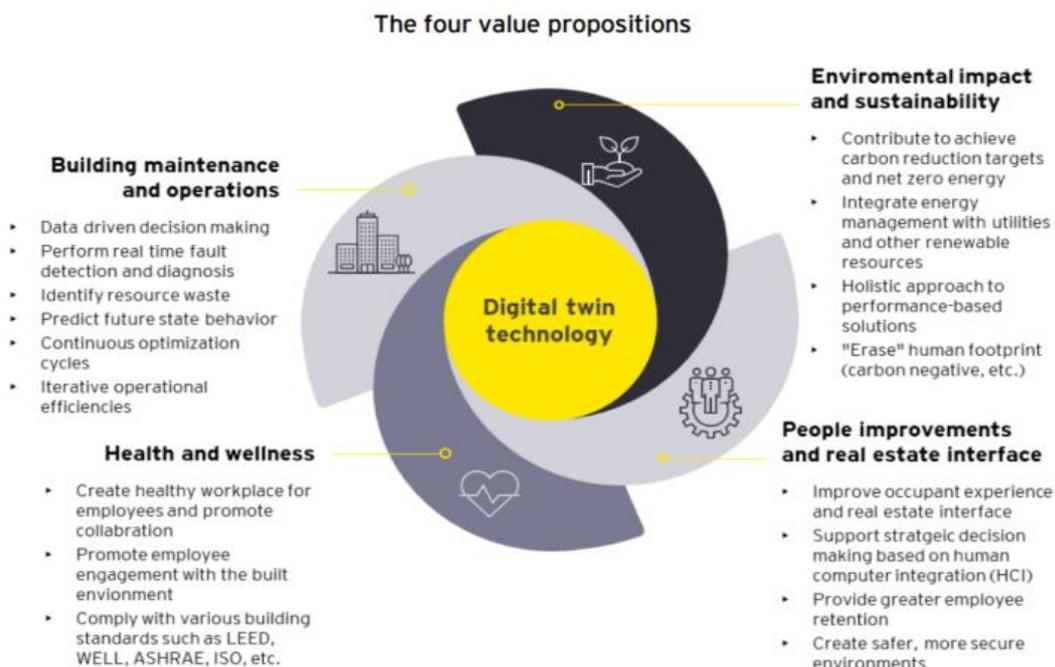


Figure 10 – Digital twin uses in AEC industry by EY

The EY presented a framework for the digital twin which is a linear system in which is not a detailed explanation of the digital twin but provides a glimpse of digital twin utilization in the built environment.

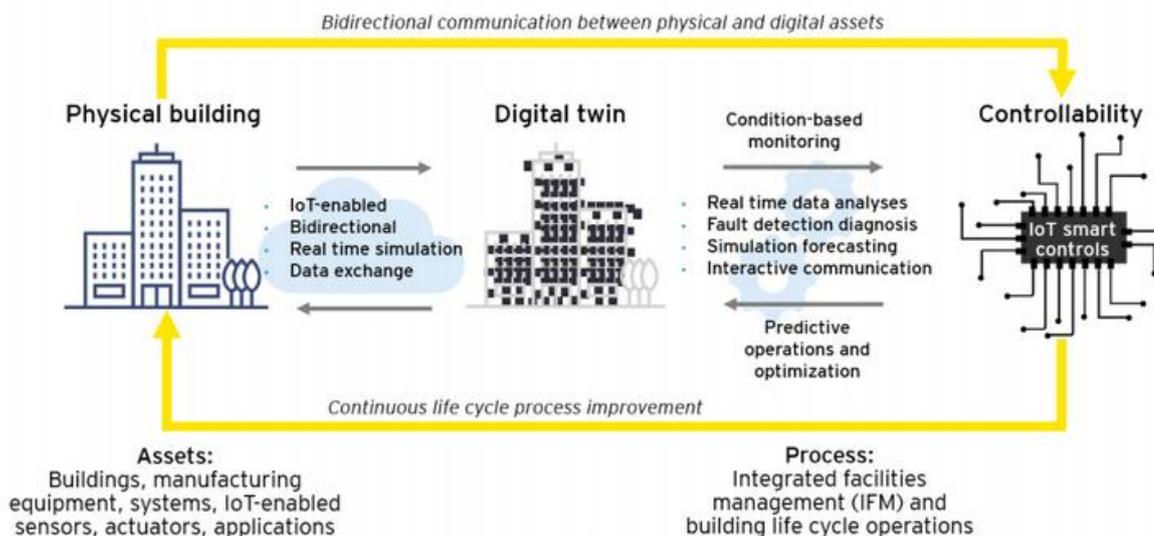


Figure 11- Digital twin framework for Built Environment by EY

There are several frameworks for digital twin presented by researchers over the years in the built environment domain. Most of these frameworks provide their approach to connect the physical object with the virtual and then leverage the data from there.

In general, there are four types of Digital twin models:

- Interface-oriented
- Prototypical
- Model-based
- Service-based

Interface-oriented Digital Twin:

Interface-oriented digital twins are mainly used for the monitoring of the objects or assets life cycle, and data for manufacturing or re-engineering purposes. The implementation of it is difficult in the AEC industry as the data or information exchange is quite abstract and the layers of information aren't clearly defined. It provides an interface between the physical and virtual object but the explicit link between these two is not clear. These types of DTs are not suitable for individual asset information recovery or data input.

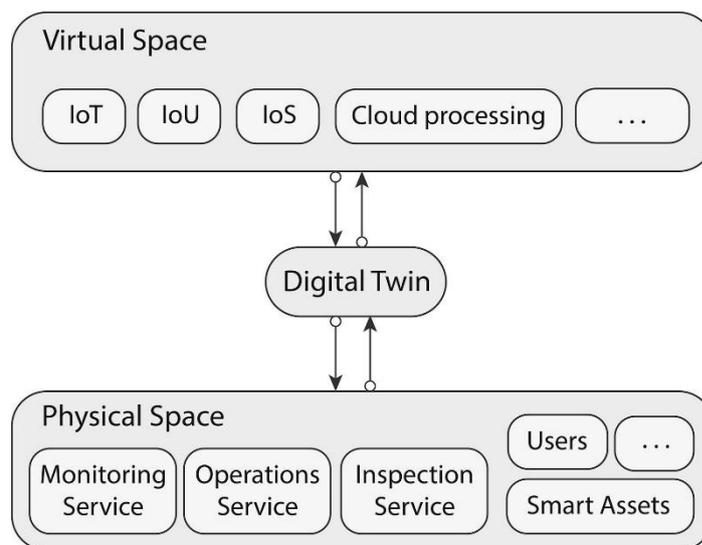


Figure 12 – Interface oriented DT framework abstracted from (Y. Wang et al., 2020; Zheng et al., 2018)

Prototypical Digital Twin:

These types of DTs provide more detailed data from the physical assets and can be linked to the Building Management Services or systems (BMS). Apart from the usual capability of sharing the operations and maintenance data, these DTs can also provide periodic data for events or occurrences as defined by the use or DT owner. Prototypical DTs take into account the asset's life cycle as well as use-case descriptions. Regarding Built environment applications these DTs can be deployed in parallel with BMS solutions and monitoring protocols (P. Wang et al., 2021). All sorts of stakeholders (Operators, owners, authorities, and end-users) can interact with the DTs. Contextual visualizations are included in the list of DT services because the context in which an item is located is extremely important for built assets.

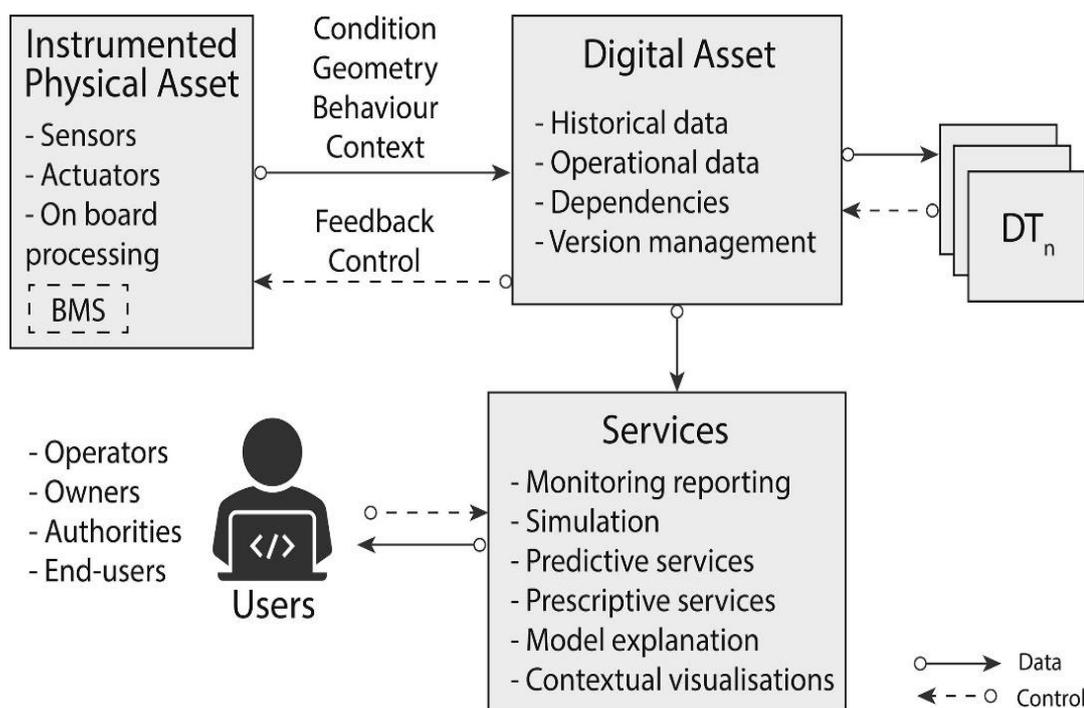


Figure 13 – Prototypical DT framework inspired from (Ashtari Talkhestani et al., 2019; M. Liu et al., 2021; Q. Lu et al., 2020)

Model-based Digital Twin:

Model-based DTs are quite like the BIM concepts and are used for assets that require a higher degree of a digital replica of complex physical objects/structures. To effectively depict the changing conditions of the physical asset, proper interaction between the various models is required (Miller et al., 2018). It is important to note that the Model-based DTs require a higher degree of precision, communication, and interoperability protocols, and every 4 nodes mentioned in the below model are fully integrated. DT model will have four different nodes enabling its functionality, the function of the 4 nodes is as follows.

- i. **Configurator node:** It is a user interface that allows various categories of users in the built environment to customize the DT's structure, functionalities, and control rules.
- ii. **Ontologies node:** It is a collection of components and resources used to customize certain DTs to meet the needs of the user
- iii. **Simulation node:** Various Algorithms play their role here. This process or node evaluates and simulates the performance of various DTs.
- iv. **Visualization node:** This is a visual environment that provides a visual presentation of simulations and evaluations that have been completed.

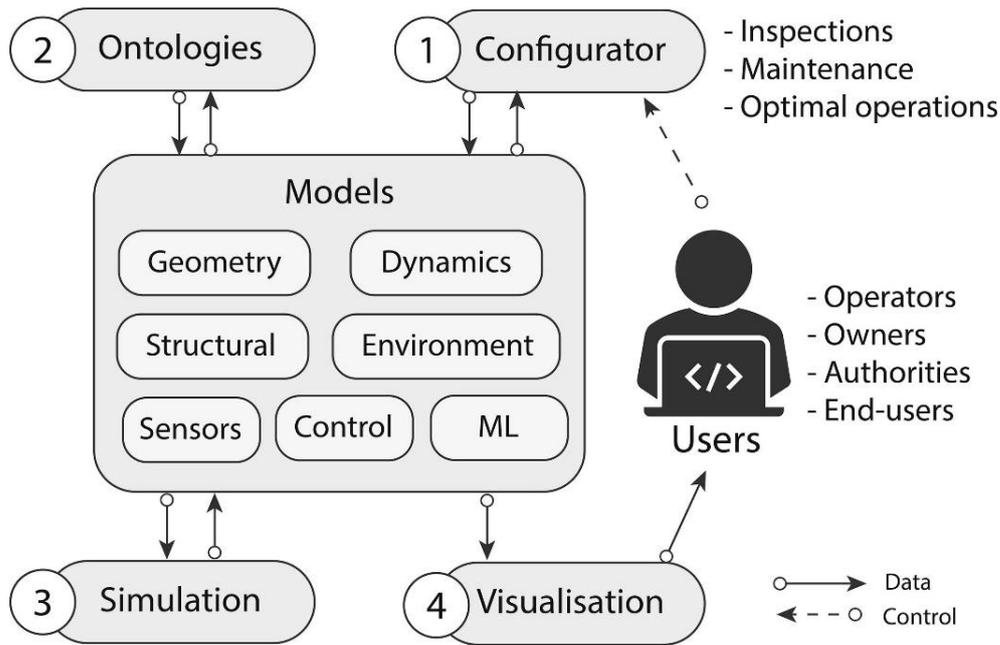


Figure 14 - Model based digital twin (Tao et al., 2018; Terkaj et al., 2019; Vrabčič et al., 2018; Zhang et al., 2019)

Service-based Digital Twin:

These types of DTs are usually developed to manage the construction and operation of large-scale complex assets. For example, nuclear facilities, manufacturing units, oil, and gas refineries. These DTs aim to automate the complex workflows in which the user takes the central position (Aheleroff et al., 2021). Through this real-time monitoring, control, and maintenance services of a complex system can be handled manually or through automation. Service-based DTs enable the user to handle an array of isolated or interconnected DTs. These DTs are modeled in an explicit manner in which data workflows are rather complex but provide a better virtual representation of the physical asset.

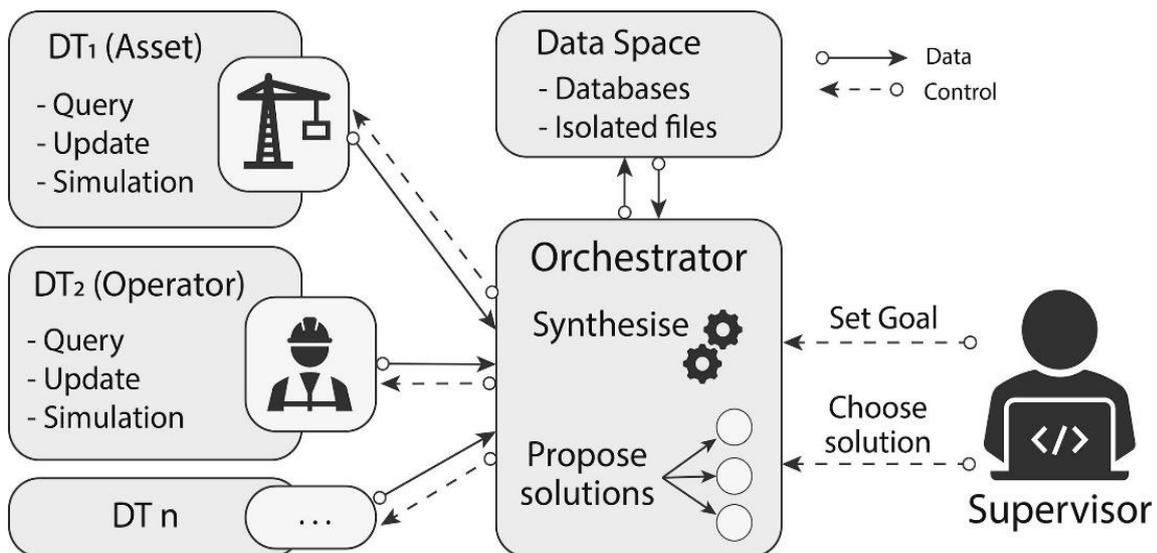


Figure 15 – Service-based Digital twin (Catarci et al., 2019)

(Boje et al., 2020) concluded that the data information exchange has been made easy by the introduction of IFC but still a lot of barriers are there to harness the true potential of the digital twin. However, (Bilal et al., 2016) concluded that most of the studies are related to operations and maintenance of few key parameters for facility management. A research study (Ye et al., 2019) proposed a digital twin model for structural health monitoring. The digital twin concept is also getting popularity for the management of urban assets a research study conducted by ETH Zurich (Schrotter & Hürzeler, 2020) proposed a digital twin model for urban planning. In this study, extensive use of spatial data and the data from the physical objects were synced to create a digital twin for Zurich. The use of digital twin is also getting to measure and evaluate parameters related to the indoor environment quality, occupant's behavior, facility management to predict the behavior of parameters. An occupancy-oriented Digital Twin (DT) study was conducted to evaluate the factors and optimize the operational phase of the buildings (Seghezzi et al., 2021). This study is aimed to produce a Building Management System (BMS) for facility management based on occupancy DTs. IoT, cameras, sensory devices, and advanced data modeling techniques were used to obtain the results from the Digital twin. Indoor air quality predictions for the educational building were made by using sensory data (Tagliabue, Re Cecconi, et al., 2021). These predictions can be used to further optimize the building operations by adjusting the HVAC systems. The approach adopted in this research can be used to measure various other factors of the indoor air quality ranging from temperature to measuring the accumulation of volatile organic compound (VOC) accumulation. Some parameters have already been measured in this research. Similarly, by harnessing the potential of forecast and anticipation through data processing an approach for the smart built environment was presented in the research (Tagliabue, 2021). Furthermore, a case study-based research (Tagliabue, Cecconi, et al., 2021) presented an approach in which the concepts of Green BIM along with the DTs were used to conduct the sustainability assessment for the educational building was done. It concluded that the development of DTs and the data analytics during the use phase allows for better building management and real-time sustainability evaluation. Digital twin enhances the decision-making capability of the stakeholders and facility managers. It allows them to perform what-if scenarios on the operational phase of the building and then optimize the operational energy of the building (Khajavi et al., 2019). The data of the digital twin is quite useful and not only for the building for which it was developed but this data can also be used for big data analytics to study the behavior of future projects (Qi & Tao, 2018).

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3. RESEARCH RATIONALE

The literature review provided an insight into the BIM, sustainability, and digital twin domains of the built environment. The important takeaway from the literature is that the impact and uses of the digital twins are immense considering the existing and futuristic needs of the AEC industry. Although the majority of the industries are using the digital twin for their different needs the level of maturity, data integration, and standardization of digital twins varies a lot. Most of the solutions are customized. Similarly in the construction industry, the concept of the digital twin is making significant inroads and proved to be useful in terms of operation and maintenance, energy management of the building, and other user-centric simulations. A bibliographic research study (Opoku et al., 2021) conducted that most of the research studies on digital twins are in the use phase of the built environment as that data during the use phase is important for facility management. Apart from the buildings, sectors various studies have been carried at the city level to harness the potential of the digital twin.

City-level digital twin application was tested on the West Campus of the University of Cambridge, UK. The aim and objective of the study were to measure urban resilience in terms of sustainability parameters. The research results provided the foundation for integrating the city scale data to optimize the city services. Furthermore, it also provides better insights into the urban system's behavior over time and a useful data repository for future planning. However, on the other hand, it revealed that there are major challenges in implementing digital technologies at a large scale.

3.1. Need for Green Digital Twin.

There are various reasons to have a dynamic digital twin for sustainability assessment. The need arises from the initiatives to achieve SDGs globally and locally. The European Union (EU) Green Deal is a comprehensive ambitious plan to reduce carbon emissions. The role of the built environment in reducing emissions is immense. Sustainability in buildings is measured on a range of parameters and factors. Green building rating systems serve as a foundational block to quantify the sustainability parameters. Each category is further divided into points and each point has its criteria to be fulfilled. Based on the points achieved, a certification is awarded to establish the measures taken to make a building more sustainable. However, the green building rating systems are diverse and the categories cover a range of building characteristics. All these characteristics are parameters that can be made dynamic through the use of sensors and other techniques.

The need for the development of a dynamic digital twin is evident considering,

- Building, either certified or not certified, is a living element or object producing a lot of data that can be used for various purposes.
- Parameters of the green building need to be recorded reported periodically, and maintained over the life cycle of the building,
- Effectively support the built environment control and monitoring to durably evolve towards a green and sustainable dimension,

- Provide a decision support system to stakeholders based on the real performance of the buildings.
- Digital twin’s results or outputs can provide useful insights for future planning of the building for designers, owners, researchers, and building regulatory authorities.
- Digital twins can make the green building certification, recertification, and performance process efficient which is currently based on documentation review and sometimes on-field testing. For example, the certification process in LEED and WELL involves documentation review. The time, after credit submittals, in reviews, comments, etc can vary from 45 to 90 days which makes things further delay. The process is linear as shown in the figures below,



Figure 16 – WELL certification process

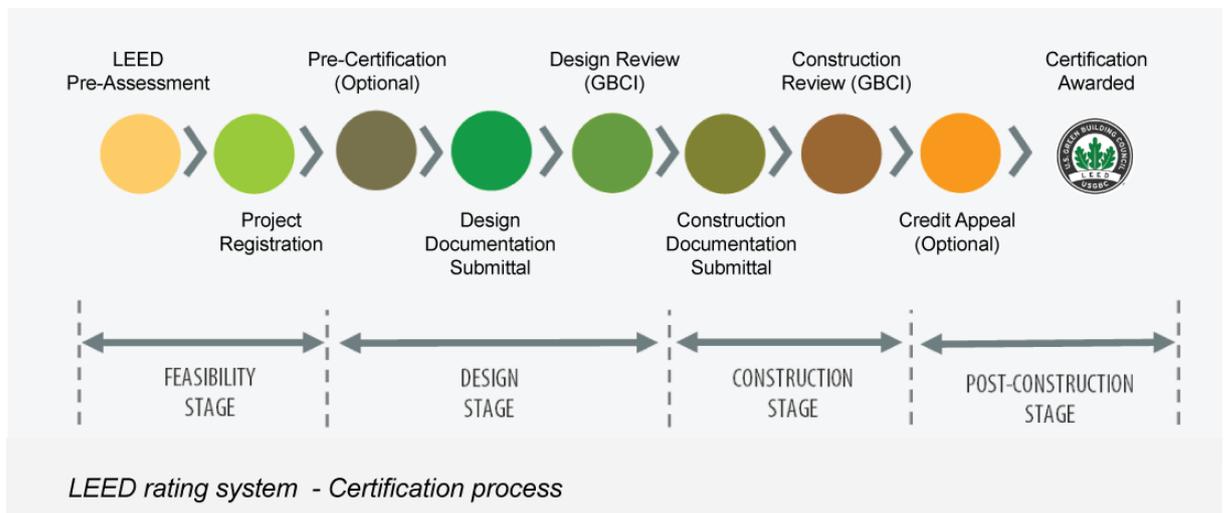


Figure 17 – LEED certification process

4. GREEN DIGITAL TWIN AND PROPOSED FRAMEWORK

4.1. Green digital Twin Basics

The foundation of a green or sustainable built environment is based on the principles of sustainability which is a bigger domain. It aims to achieve the SDGs and every industry has its methods and ways to achieve that. Similarly, the green buildings at the MACRO level consider the same attributes. The rating systems are developed in a way that upon implementation they provide environmentally friendly, economic, and socially viable solutions. The green digital twin is focusing on the parameters of the green buildings. Various green building rating systems are there and each has its own set of parameters that needs to be evaluated.

In table 2 the common green building rating systems are mentioned but here in the following table only the LEED, WELL, BREEAM, and LBC and their target areas are mentioned. The reason to present only these is that they are the most widely used ones and represent the major categories under consideration.

Table 7 - Green Building Standard and their credit categories

Building standard	Target Area
LEED	Integrative process
	Location & transportation
	Sustainable sites
	Water efficiency
	Energy & Atmosphere
	Materials & Resources
	Indoor Environmental Quality
	Innovation & Design
	Regional Priority
WELL	Air
	Water
	Nourishment
	Light

	Movement
	Thermal Comfort
	Sound
	Materials
	Mind
	Community
	Innovation
	Governance
	Social and economic wellbeing
BREEAM	Resource and energy
	Land use and ecology
	Transport and movement
	Place
	Water
	Energy
LBC	Health and Happiness
	Materials
	Equity
	Beauty

4.2. Key Performance Indicators (KPIs)

It is very important to establish the Key Performance indicators as identifying them can help to develop strategies and mechanisms for data input, processing, and output. Considering the complexity and diversity of the built environment parameters the KPIs have been divided into three layers.

- **Primary Indicators:** These are the MACRO elements and define a major field. For example, all the elements that can impact the environment by any means will come under the environment

domain and the Environmental domain will become the primary KPI. Similarly, all the elements related to human health will come under the Wellness primary KPI.

- **Secondary Indicators:** These are the ones that can be grouped under the Primary indicators or the subset of primary indicators. For example, energy generation and use directly impact the environment due to the carbon emissions associated with it. So the energy saving
- **Tertiary Indicators:** These indicators are the subset of secondary indicators and include various criteria. Tertiary indicators are the foundational block of any DT. For example, all the credits related to energy are part of tertiary indicators.

The relation between the KPIs is shown as follows.

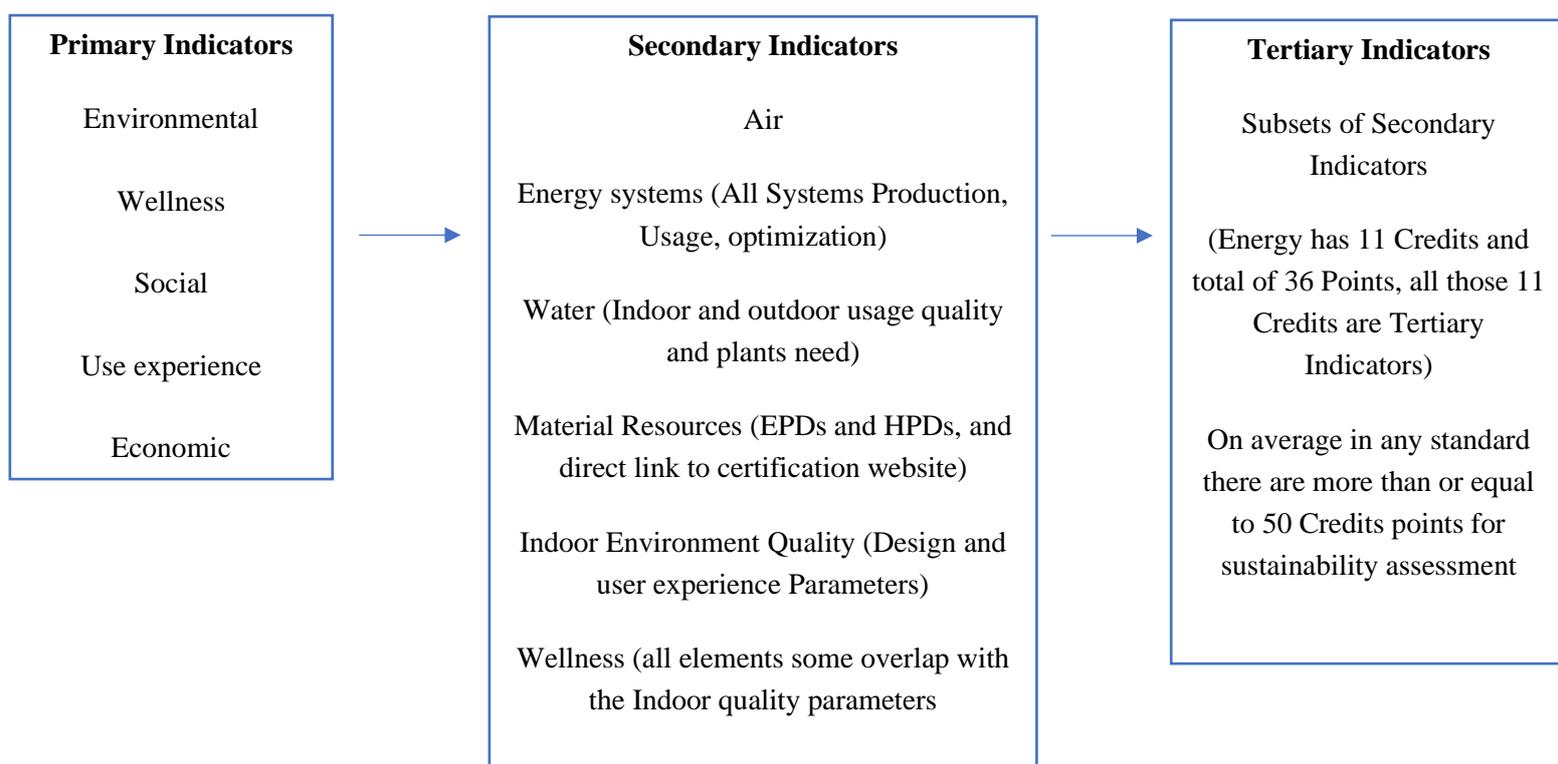


Figure 18 - KPIs and their Relation

In the case study for the green digital twin, the tertiary indicators are of prime importance and they will be the focus. The values for the tertiary indicators will be taken from the standards (LEED, WELL, LBC, BREEAM, etc).

4.3. Proposed Framework for Green Digital Twin

After the review of different studies, it is evident that the concept of the digital twin in the sustainable built environment or overall in the construction industry is not mature. It is getting popular and research studies have already proved the potential of the digital twins. A uniform approach for the development of "Digital Twins" is required. Considering the factors from the built environment perspective the Digital Twin paradigm intends to improve existing construction processes and models (nD BIMs) and their accompanying semantics (e.g. IFC, COBie) within the scope of a cyber-physical world. The scope

of these digital models will be that they will reflect the constructed physical asset at any time. Hence the concept of DT requires that the integration of construction data models with new technologies is essential to fully harness the potential of Digital Twins. In section 2.3.3 a separate discussion about the frameworks and types of DTs has been done. However, due to the complexity and diversity of built environment parameters and associated interoperability issues a single model of DTs can't be adopted. Amalgamation and customization of various DT models are required to develop a model for the DTs. A generic framework for the DT is presented below which is an effort to provide an idea about the different layers a DT can have.

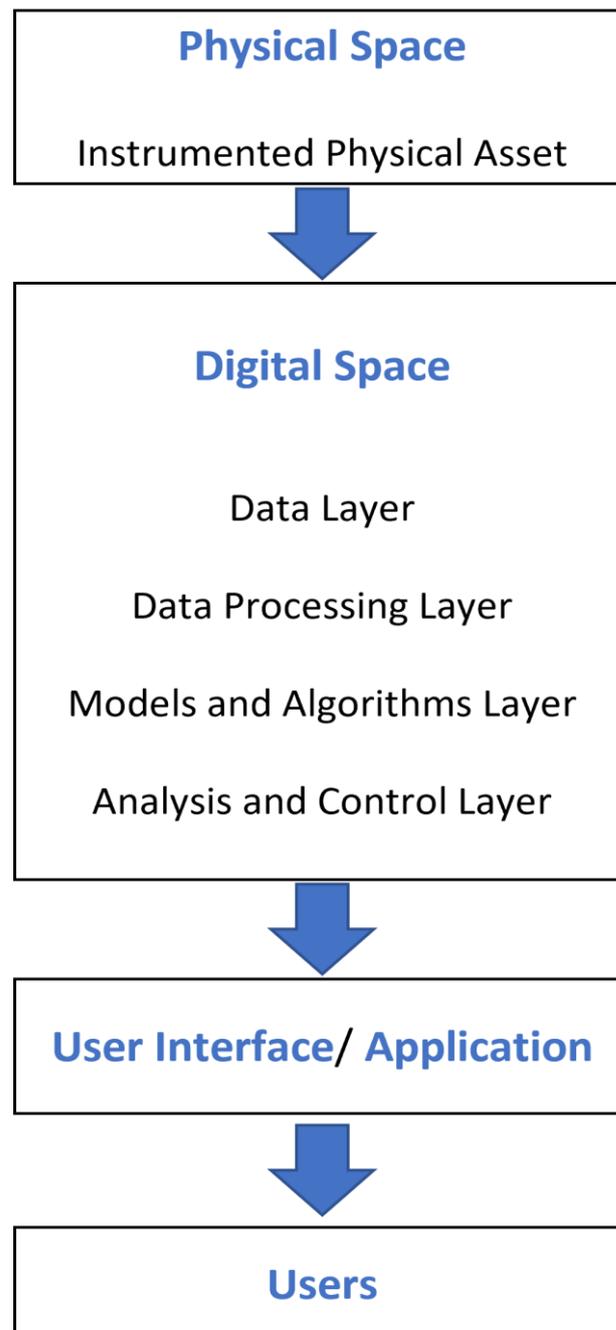


Figure 19 - Generic digital twin segments/layers and related components

A digital twin is a combination of several modules, such as a computer model, a physical model, communication services, and data analytics. These modules work in synchronization to monitor, learn, and optimize the complete system operation. However, the implementation of the digital twin concept may require new processes, methods, and novel platforms to interact with each of these modules.

Green Digital Twin for dynamic sustainability assessment can only be done by integrating the data from various sources for different sustainability parameters. The sources of information collection can be any but not limited to the real-time sensor, BMS, feedback devices at the public service use areas, cloud services, and asset management software. The asset information model is the key in the whole process that can lead to the development of the digital twin. However, the development of a federated model is highly dependent on the quality and quantity of the data that can be generated.

Data is the lifeline for any Digital Twin, considering the nature of this study in which the assessment of the sustainability parameters needs to be done it is important to identify that what kind of databases are required. Usually, there are two types of databases, static and dynamic data.

Static Data: Static data represent the information related to the parameters that are fixed and will not change over time or for a longer period. Commonly static data include the characteristics of the material data, physical features like windows, walls, and door information. Furthermore, the metadata in the BIM model can incorporate a lot of information that comes under the static data for the Digital twin. For example, warranty information, material sound absorption value, transmissivity, fire rating, U-value, operation and maintenance schedule, operation manuals, etc. If we further expand the type of static data from a sustainability assessment point of view then it will be regarding the site information, type of plants on the site, materials HPDs, and EPDs.

Dynamic Data: Dynamic data refers to all sorts of data from the building that is not constant and changing over time, randomly or periodically. Mainly dynamic data is from the IoT, sensors, and other monitoring devices placed in the buildings. For example, all the data coming from the sensors data to monitor the carbon dioxide level in any room, lighting levels monitoring sensors, occupancy sensors, HVAC speed controlling devices data, humidity monitoring data, and energy consumption data at any given time frame. Usually, this dynamic data is processed by simple algorithms or AI for simulations to extrapolate and predict the behavior of certain parameters.

The proposed framework for the green digital twin is shown below. It is a comprehensive framework that defines each layer separately and a bottom-up approach. The framework starts from the basic BIM data or model and relies mostly on the data that is fed to the either BIM model or directly to the server available. It is highly dependent on the nature of the study or the data collection method that can vary from study to study. Furthermore, sometimes the nature of the parameters under consideration can create problems regarding data interoperability, data recording, security, quality, and quantity of the data. As it is a proposed model and has the provision for the n^{th} number of digital twins but in a real case scenario it depends on the number of credits and parameters associated with those credits are being measured.

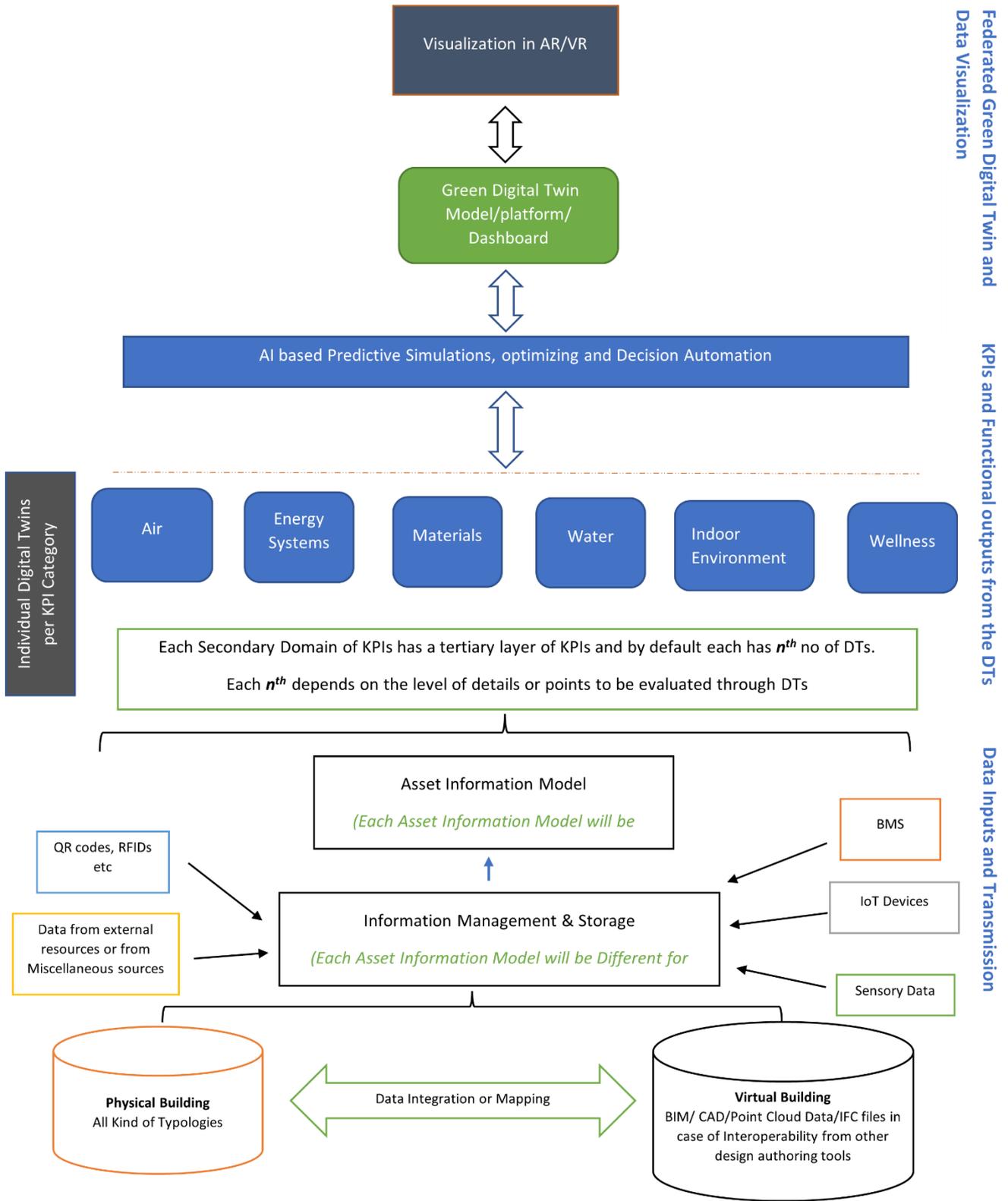


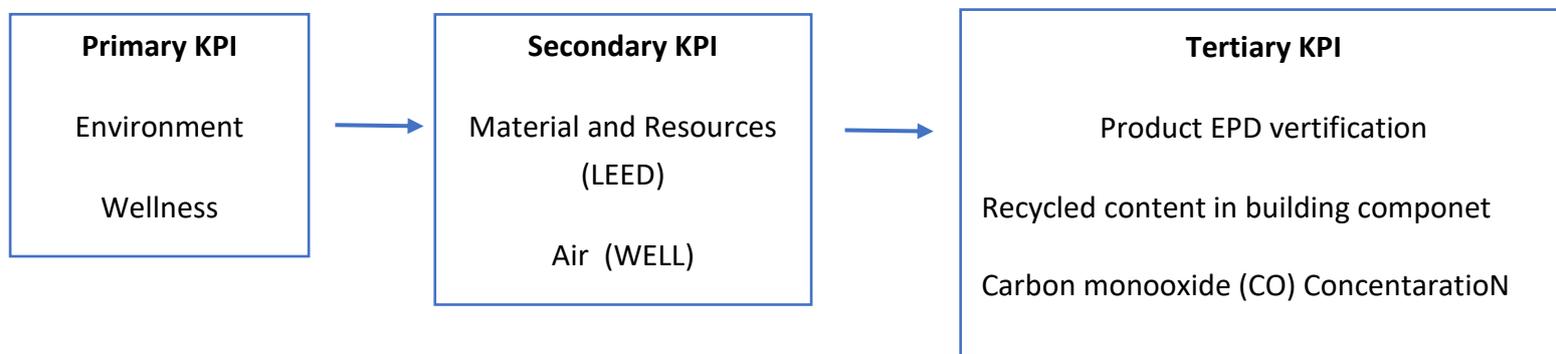
Figure 20 - Proposed Green Digital Twin Framework

5. CASE STUDY

To verify the sustainability assessment through digital twin a case study was conducted on the eLUX lab building at the University of Brescia, Italy. Although there are many parameters related to sustainability. However, for this case study, one parameter from LEED and WELL are tested through digital twin and then the visualization of the data in the Virtual Reality. The parameters that are measured are related to the,

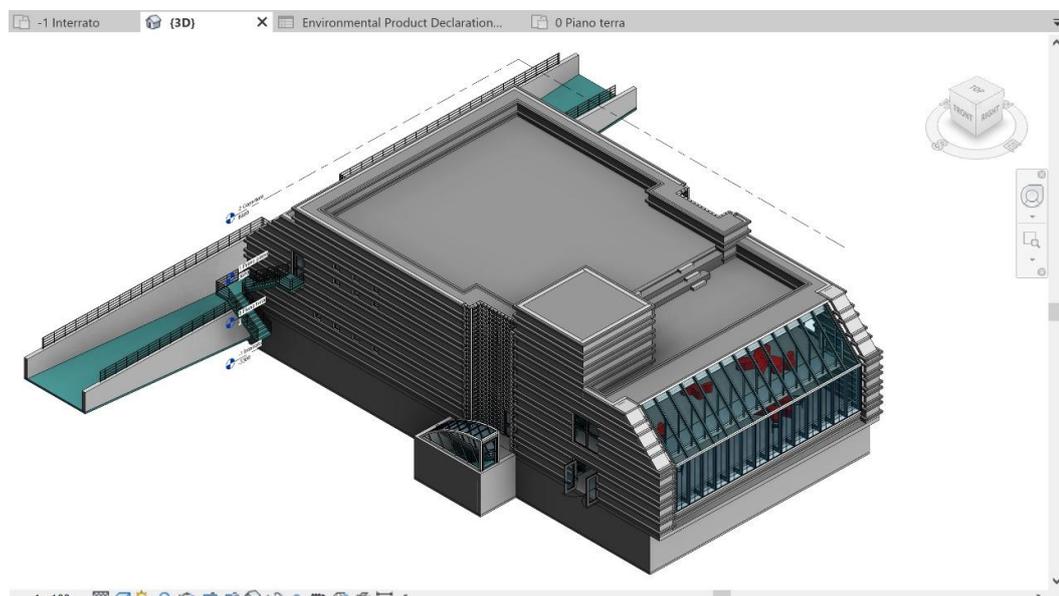
- **Material and Resources** Category from **LEED V4.1 rating system**
- **AIR** credit category from the **WELL V2 building standard**.

The relationship of the measured parameters in terms of primary secondary KPIs is shown below,

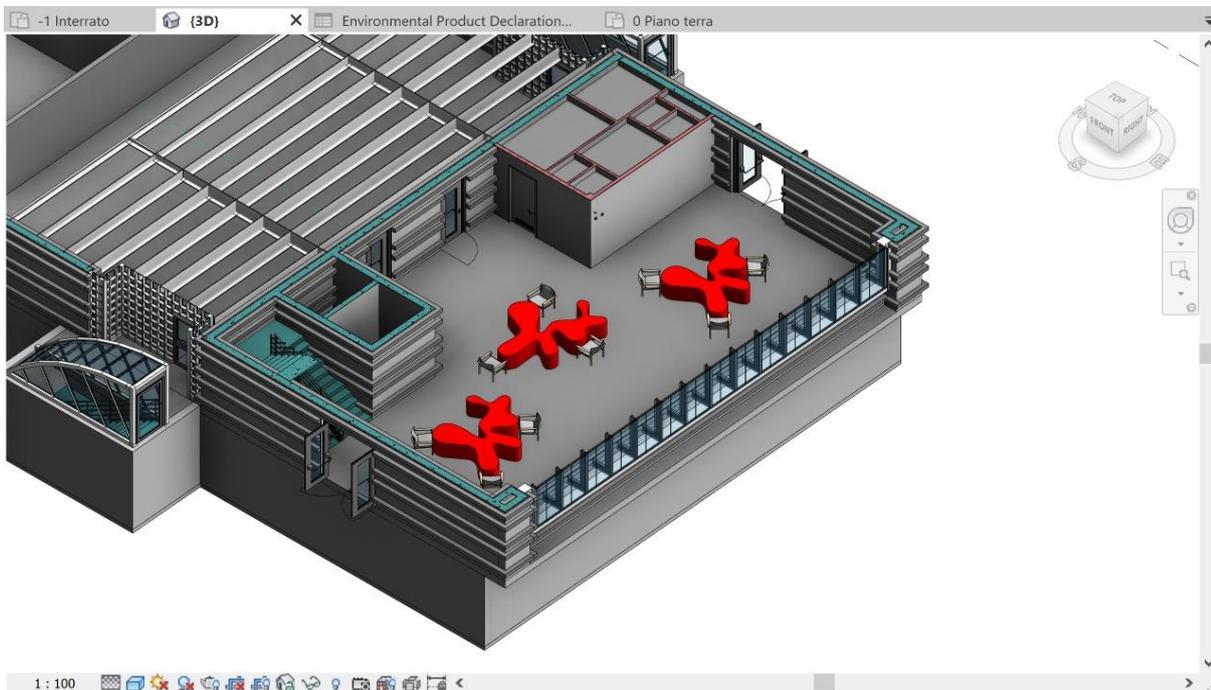


Recycled content and EPDs belong to the static data category while the CO concentration is a value that is from the dynamic data category. The Revit model for the eLUX lab is used in conjunction with the Escape virtual reality engine to visualize the result. The complete process with screenshots is explained in this section.

3D view of building under consideration is as follows.



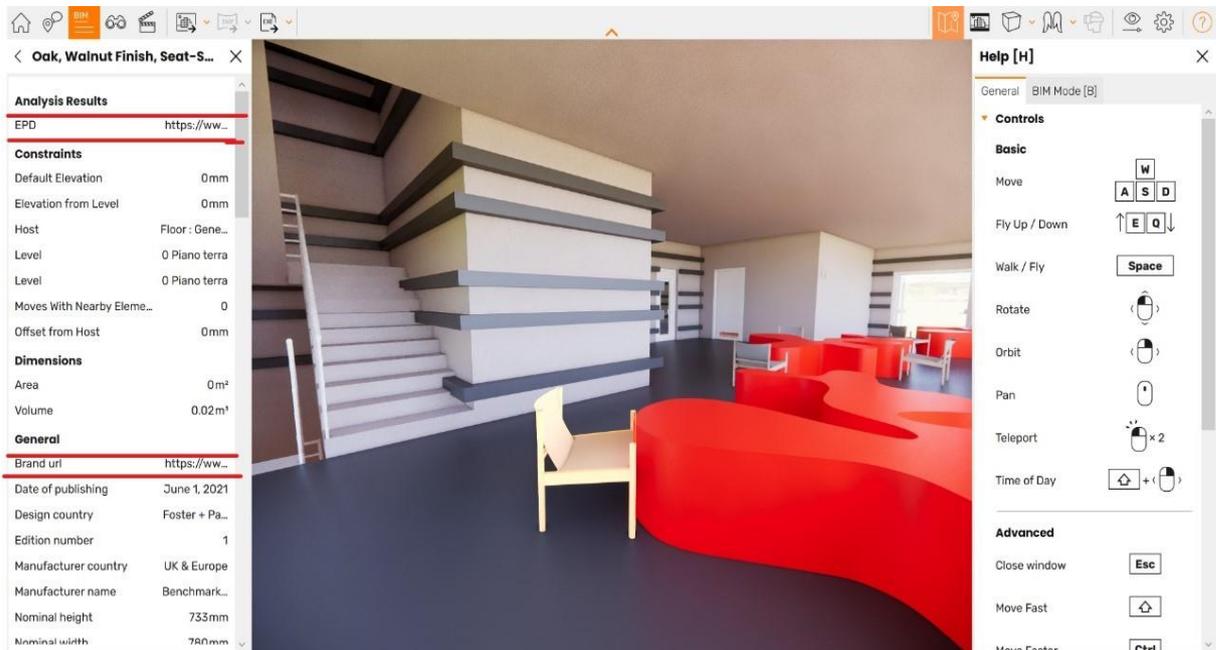
This is the 3D floor cut view of the building that is under study to measure the two parameters from the material credit category. For that purpose, our target is the furniture, chairs to be precise, and walls. A Revit family of the chair was generated and placed in the model as shown in the picture below,



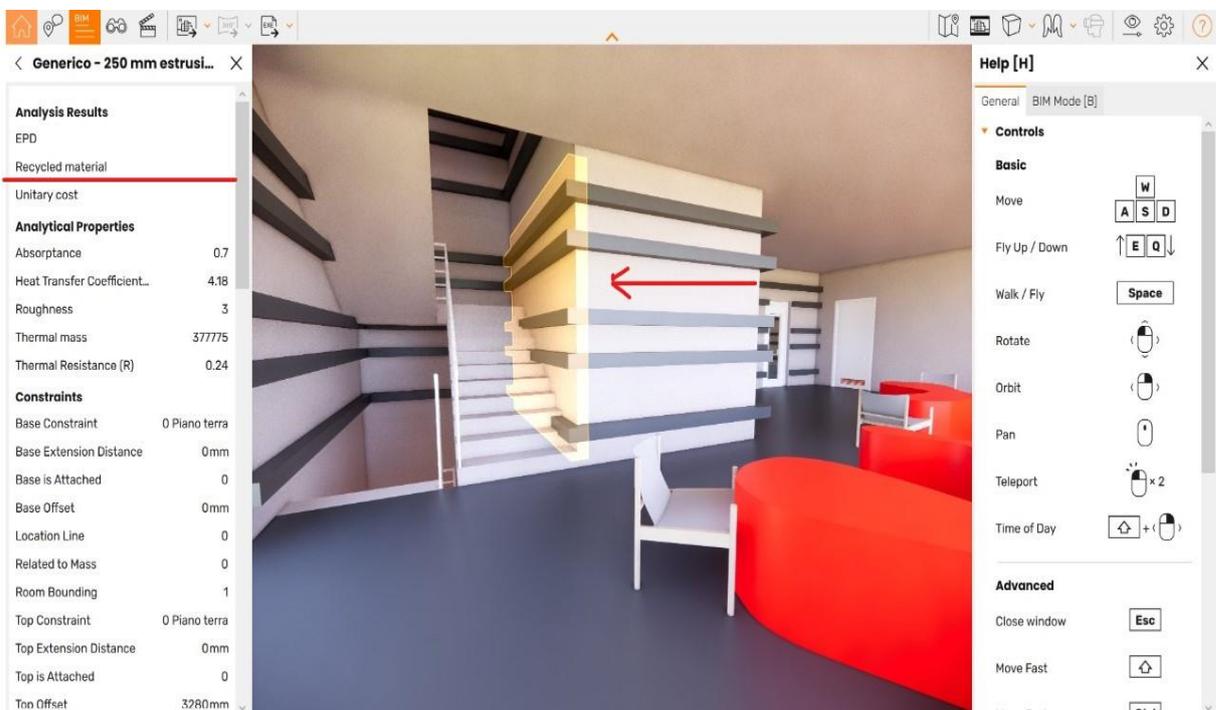
In the next step, an EPD parameter of the Chair Revit element was added and the EPD was linked in the model. The authentic EPD for the chair was selected from the international [EPD Portal](#). The image shown below is without the application of the VR engine and we can see that no information can be seen here.



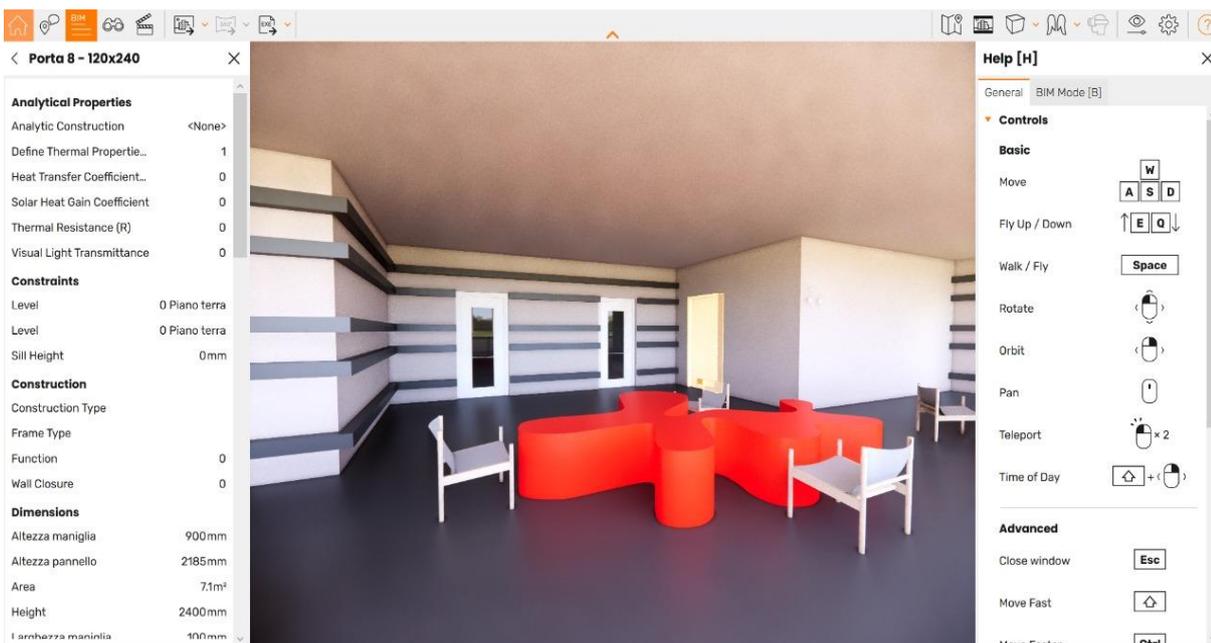
In this step, BIM data is linked with the Encaps and turned the models into immersive 3D experiences for the verification of the EPD. In the below **VR headset image** it can be seen that the color of the selected chair is yellow and the data confirms that this product is EPD verified.



Similarly, the staircase wall has recycled content and the recycled material is defined as a parameter in the BIM model for that wall. The VR selection of the image confirms the recycled content. The amount of percentage of the recycled material is unknown that's why it is not showing any value.



If we choose the other elements that don't have EPDs, the data will not show that they are EPD verified. In both, the images below the door and roofing are selected but they aren't showing any data value.

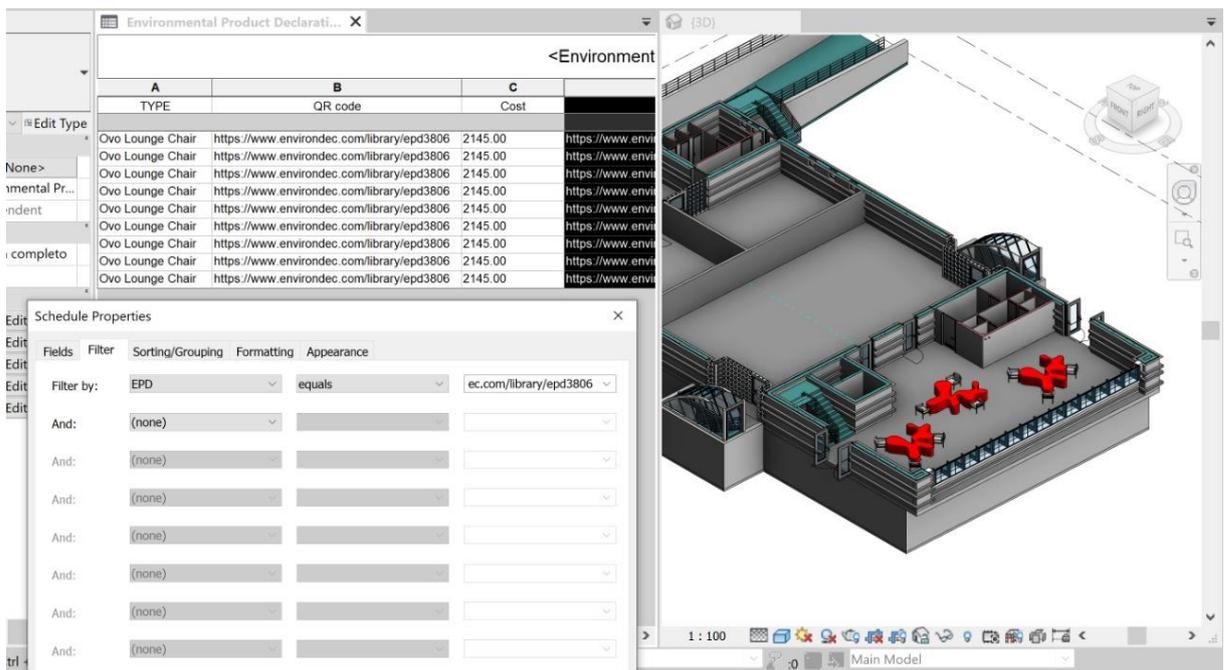
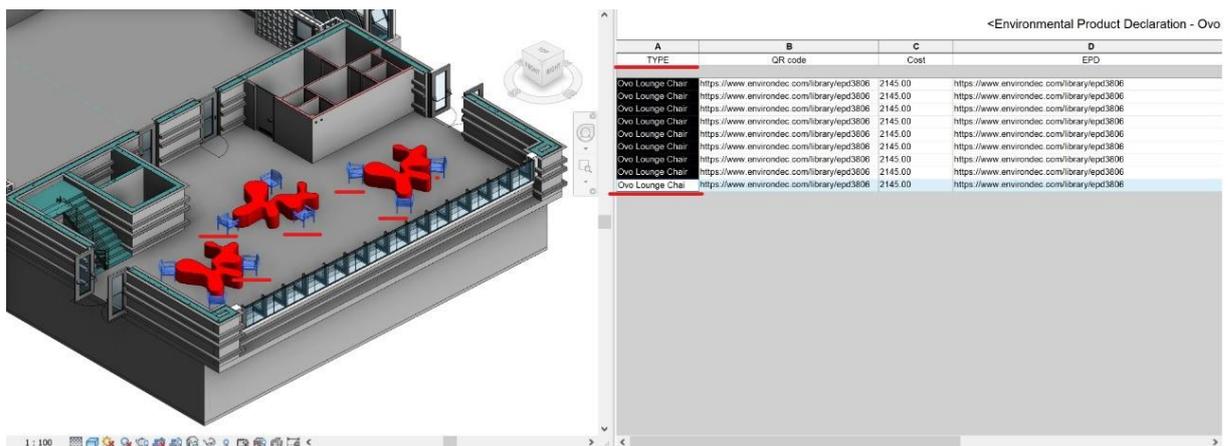


This is how we conduct the sustainability assessment of the building components by harnessing the potential of the BIM data and then using the virtual reality engine. It is important to remember that the BIM data is the basis of the sustainability assessment.

Now moving on to the next scenario in which the same EPD verification is being done but in the BIM environment. Furthermore, by selecting the object in the BIM and using the filter option in BIM schedules we can see in the following pictures that all the chairs with the EPDs are selected. The purpose of filtering, selecting, or verification within the BIM environment is to highlight the fact that the

metadata of the BIM model, objects, or elements is of prime importance. The following figures show the EPD metadata of the chair in the BIM model, and then the selection of all chairs that are EPD verified.

Environmental Product Declaration - Ovo Lounge Chair						
TYPE	QR code	Cost	EPD	Design country	Manufacturer name	Manufacturer country
Ovo Lounge Chair	https://www.environdec.com/library/epd3806	2145.00	https://www.environdec.com/library/epd3806	Foster + Partners, UK	Benchmark Woodworking Ltd	UK & Europe
Ovo Lounge Chair	https://www.environdec.com/library/epd3806	2145.00	https://www.environdec.com/library/epd3806	Foster + Partners, UK	Benchmark Woodworking Ltd	UK & Europe
Ovo Lounge Chair	https://www.environdec.com/library/epd3806	2145.00	https://www.environdec.com/library/epd3806	Foster + Partners, UK	Benchmark Woodworking Ltd	UK & Europe
Ovo Lounge Chair	https://www.environdec.com/library/epd3806	2145.00	https://www.environdec.com/library/epd3806	Foster + Partners, UK	Benchmark Woodworking Ltd	UK & Europe
Ovo Lounge Chair	https://www.environdec.com/library/epd3806	2145.00	https://www.environdec.com/library/epd3806	Foster + Partners, UK	Benchmark Woodworking Ltd	UK & Europe
Ovo Lounge Chair	https://www.environdec.com/library/epd3806	2145.00	https://www.environdec.com/library/epd3806	Foster + Partners, UK	Benchmark Woodworking Ltd	UK & Europe
Ovo Lounge Chair	https://www.environdec.com/library/epd3806	2145.00	https://www.environdec.com/library/epd3806	Foster + Partners, UK	Benchmark Woodworking Ltd	UK & Europe
Ovo Lounge Chair	https://www.environdec.com/library/epd3806	2145.00	https://www.environdec.com/library/epd3806	Foster + Partners, UK	Benchmark Woodworking Ltd	UK & Europe
Ovo Lounge Chair	https://www.environdec.com/library/epd3806	2145.00	https://www.environdec.com/library/epd3806	Foster + Partners, UK	Benchmark Woodworking Ltd	UK & Europe



From the verification of the material EPD and recycled content, we can say that the establishment of a cyber-physical world connection can help verify the sustainability parameters. Hence validating the Green Digital twin for the material credit category.

The WELL building standard Air category parameter carbon mono oxide concentration was monitored, analyzed, and shown in the BIM model. According to the standard, the concentration of the CO must be less than 9 PPM in any given space. This data can be monitored in various ways, analyzed and results can be shown in the model. However, here the results are only shown in the changing colors to show that how the color scheme of the spaces will change based on the CO concentration levels. In further advanced studies, it can be linked with the alarms or HVAC systems to induce the fresh air or exhaust mechanism to keep the CO concentration in range.



6. CONCLUSIONS

Based on the case study and the proposed green digital twin framework it can be concluded that the process of sustainability assessment through digital twin is highly dependent on the BIM and other input data. The sustainability parameters assessment is quite efficient, fast, and transparent through Digital twin. Each parameter of sustainability has its requirement for the digital twin. Hence each digital twin will be unique in its structure and might have the same or different components and layers of the digital twin framework with respect to the other digital twins.

Considering the wide applications of the green digital twin the following conclusions can be inferred from the research study. The development and implementation of Green Digital twin can be used

- To facilitate the transition of sustainability assessment from the static approach to the dynamic approach. With sensors, IoT devices, and other tools various parameters can be digitalized.
- Monitoring and evaluating the building performance over the years to periodically report the performance of green buildings especially the Energy and Atmosphere credit which is the requirement by the LEED, and AIR credit parameters regarding human health and air quality that needs to be periodically reported.
- To provide better data management, sharing, and reporting mechanism to apply for renewal of certification as per the conditions of the rating systems used. It can make the process more easy, fast, efficient, and transparent.
- Improving the Green Building certification process. With digital twin review, comments and credit verification will be fast.
- Leveraging the data of digital twin for predictive analysis, simulations, evacuations, safety, and other emergency response planning.
- Data visualization in Augmented Reality (AR) and Virtual Reality (VR) itself is a powerful domain and is not an integral part of the digital twin, but can be linked with the data for visualization of simulations results. For example, the Airflow simulations result can be visualized in a VR environment for decisions and occupant's planning (sporting events or emergency response. AR/VR can also be used for WELL and LEED features (lighting, thermal comfort, airflow modeling, and quality views) verification.

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LIST OF ACRONYMS AND ABBREVIATIONS

AEC	Architectural, Engineering, Construction
AIA	American Institute of Architects
AI	Artificial Intelligence
API	Application Programming Interface
AR	Actual Reality
BIM	Building Information Modelling
BMS	Building Management System
BREEAM	Building Research Establishment Environmental Assessment Method
CIB	International Council for Research and Innovation in Building and Construction
DT	Digital Twin
EY	Ernst&Young
GDP	Gross Domestic Product
GHG	Green House Gasses
IFC	Industry Foundation Classes
IoT	Internet of Things
KPI	Key Performance Indicators
LCA	Life-Cycle Analysis
LEED	Leadership in Energy and Environmental Design
LOD	Level of Development
SDGs	Sustainable Development Goals
USGBC	U.S. Green Building Council
VR	Virtual Reality

VOC	Volatile Organic Compound
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WGBC	World Green Building Council
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APPENDICES

Appendices include, for example, questionnaires, analysis tables, documents used, etc. They are to be marked with the sequential number and appropriately titled (e.g. Appendix 1: Title of Appendix 1). The titles of the Appendices are to be written in the same way as the titles of chapters.

APPENDIX 1: TITLE

APPENDIX 2: TITLE