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CONSTRUCTION 4.0: WHAT WE KNOW AND WHERE WE ARE HEADED?

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SUMMARY: *The last decade has witnessed unprecedented changes in the technologies and processes involved in the construction industry. The philosophies associated with Industry 4.0 now reverberate in construction 4.0. Digitalization and interconnectivity in the cyber-physical systems of the sector are at the heart of such transformation. Construction 4.0 brings to the table a plethora of technologies and associated processes over the construction project lifecycle. The current study performs a state-of-art literature review to summarize the knowledge advancement in construction 4.0. A layered conceptualization spanning across project lifecycle utilizing the people-process-technology dimensions is presented to summarize the current understanding of Construction 4.0. The cyber-physical space is classified into the physical, digital tool, data, and core data security and interoperability layers. The inter-layer and intra-layer interactions and information flows are then conceptualized based on the extant literature, including the human interaction and interventions. The people-process-technology dimensions were discussed across the project lifecycle through interactions in these layers. It is observed that Construction 4.0 is set to be driven by data creation, data flow, data transformation, and data storage across the project lifecycle to ensure a collaborative environment across the stakeholders who interact and associate with different layers of Construction 4.0. The article finally presents challenges with the current formulations and explores ways to further our knowledge in the area.*

KEYWORDS: *Construction 4.0, People-process-technology framework, State-of-art frontiers in construction, Digitalization Technologies*

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1. INTRODUCTION

The construction industry is a significant employment generator in many countries and an essential contributor to their economic development. It should be noted that the construction industry contributes to about 13% of the world's Gross Domestic Product (GDP). However, it is a matter of concern that the value added by construction worker averages about $25 per hour globally that is significantly lower that the global average of $37 per hour for all the sectors. Therefore, significant challenges lay in the path of improving the construction sector productivity and innovation (McKinsey Global Institute, 2017). The advent of disruptive technologies, especially in cyber-physical systems, promises a notable positive impact on the construction industry. Industry 4.0 is already well established in the manufacturing and production sectors (Boyes *et al.*, 2018). The equivalent adaption of automation and digitization in the Architectural, Engineering, Construction, and Operations (AECO) industry is Construction 4.0 (Craveiro *et al.*, 2019). Apart from the evident productivity gains, Construction 4.0 also promises synergies with Lean construction concepts, Integrated Project Delivery through increased collaboration among stakeholders, and utilization of the digital twin technologies (Lekan *et al.*, 2020). Further, the use of Building Information Modelling (BIM) combined with Augmented and Virtual Reality (AR/VR) – essential components of Construction 4.0 help in the reduction of wastes and contributes to sustainable infrastructure management as well (Global Alliance for Buildings and Construction, 2018). The construction sector now lies at an exciting crossroads of implementing such technologies. Several research studies furthered our understanding of our knowledge and demonstrated the potential benefits of using such disruptive technologies. It is imperative to summarize the knowledge so far and understand the challenges and the research directions in mainstreaming the Construction 4.0 paradigm. In the current study, the current research trends in Construction 4.0 are summarized with the aid of a project lifecycle-based people-process-technology framework. To this end, the article is organized as follows. First, the fundamental philosophy of Construction 4.0 originating from Industry 4.0 is discussed. Second, the conceptualization of the paradigm and the research across the project life cycle phases is summarized. Subsequently, the challenges to adoption and the future research directions in Construction 4.0 are discussed

2. INDUSTRY 4.0 AND TRANSITION TO CONSTRUCTION 4.0

The latter half of the twentieth century witnessed the advent of digital technologies in the manufacturing and production sectors, usually termed Industry 4.0 (Zabidin, Belayutham and Ibrahim, 2020). The surge of numerically controlled electronics-based systems that supported digital designs, mass production in the industry led to this IT-based automation. Networking and connectivity are the cornerstones of Industry 4.0. It features seamless data synchronization and communication between the machines through the Internet of Things (IoT). Human interventions are reduced by a significant amount in the new paradigm (Kling and Turk, 2019). The advancements in the use and adoption of technology are considerably laggard in the construction sector. This nature can be attributed to the unique challenges faced by the industry in terms of labor-intensive processes and uncertainty in project implementations. Further, the construction industry experiences significant fragmentation in various dimensions that serve as barriers to innovation (Sawhney *et al.*, 2020). Thus, a slow rate of transformation is usually witnessed in this sector, underlining the complexity of the industry and its conservative nature to disruptive changes (Forcael *et al.*, 2020). *Construction 4.0* was coined in the first decade of the twenty-first century (Lasi *et al.*, 2014). Construction 4.0 signifies the adoption of digital technologies in the construction sector. It should be noted that a majority of the industry still hovers in the third stage of the construction revolution (Construction 3.0). The newer paradigm has garnered significant attention among researchers, thus furthering the conceptualization associated with Construction 4.0 (Forcael *et al.*, 2020)

2.1 Key Drivers of Construction 4.0

The key drivers of construction 4.0 are the various digital technologies and their interaction with each other Extant research has noted both the adoption of technologies and concepts from different sectors and dedicated technologies of the industry as significant drivers. BIM holds the central position and has become the basic necessity for the construction industry's journey of creating digital twins (Boton *et al.*, 2020; Winfield, 2020). The use of various technologies (often in conjunction with BIM) was explored in extant literature. A few examples include but are not limited to the use of Virtual and Augmented Reality, Unmanned Aerial Vehicle (UAV) Systems, Internet of Things (IoT), Blockchain, Additive manufacturing, Laser Scanning technologies, and Radio Frequency Identifications (RFID) (Forcael *et al.*, 2020). These technologies were augmented using Artificial Intelligence (AI), Machine Learning (ML), Big Data Analytics, and Cloud Computing. Systematic reviews in Construction 4.0 (Boton *et al.*, 2020; Forcael *et al.*, 2020; Schönbeck, Löfsjögård and Ansell, 2020; Kozlovska, Klosova and Strukova, 2021) indicate the central nature of BIM usually enhanced and augmented by applications of AR/VR, RFID, and other digital technologies.

2.2 Objective and review method

Given the early phases of implementing this new paradigm, there is an imminent need to understand the conceptualizations involved. Further, the wide variety of technologies being employed implores the integration, interaction, and synergies among these technologies and components. Finally, the implementation and impact of Construction 4.0 across the project lifecycle need to be explored. The current study aims at answering these questions by laying the initial canvass on the implementation and conceptualizations associated with Construction 4.0. To this end, an exhaustive review of the extant literature was performed. Keyword search associated with "Construction 4.0", "digitalization", "automation", "AI/ML", "BIM" etc. was performed on SCOPUS, SCI and Google scholar databases. The articles so found were then scrutinized manually to assess the applicability to the current objectives. The articles were also searched using forward citations and snowball approaches. After the search and filtration, 109 articles were chosen to form the basic review article database. A thematic literature review was then performed, and additional supporting articles on these themes were also explored. Thus, the review provided some key intuitions on the conceptualization, implementation, and interaction among various components that make up construction 4.0. The key ideas from the review are presented in subsequent sections.

3. CONCEPTUALIZATION OF CONSTRUCTION 4.0 – A LAYERED MODEL

Construction 4.0 can be conceptualized as a layered model, as illustrated in Figure 1. The associated dynamics of Construction 4.0 can be visualized as a four-layered model, as illustrated in Figure 1. The fundamental conceptualization is the presence of a physical and three digital world layers. These are the major conceptualizations of the Construction 4.0 paradigm. The core layer is the physical layer in which the final constructed facility is located. As the project progresses from conceptualization towards operations, increasing amounts of information are created and transformed, creating the data layer of the project. The data layer and physical layer are mediated by the digital tool layer that contains technologies and tools to translate and transfer information between the physical and the data layers. Increasingly, the construction industry recognizes the importance of a core cyber-security layer that spans across lifecycle concerning data security, privacy, and ownership.

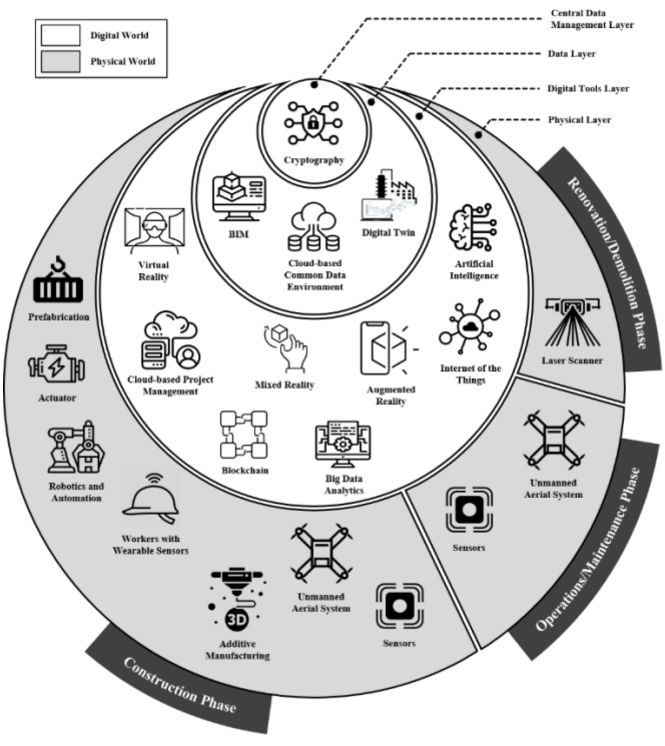

FIG. 1: The "world-view" of Construction 4.0 and its key components

The *physical layer* is where the actual material activities occur with the involvement of people during the project lifecycle. The physical world is the host for the constructed facility and contains the technologies which manipulate and(or) capture the physical reality into the data world. Hence, the technologies such as robotics and automation, wearable sensors, IoT related devices, prefabrication technologies, and processes related to additive manufacturing, including 3D printing. Further, the physical layer also interacts with technologies that capture the physical reality, such as Unmanned Aerial Vehicle (UAV), Sensors related to structural monitoring, and technologies like Light Detection and Ranging (LIDAR). The physical world is the core focus of any project. With the emergence of Construction 4.0, the digital world has risen to prominence as well. This outer layer is deeply connected with the three other inner layers, which form the digital world.

The digital world can be classified into three layers. The core layer in the digital world is the *data layer*. This layer consists of the data models that correspond to the physical world. The concepts and technologies corresponding to BIM, Digital Twin, and Common Data Environment (CDE) are the core drivers in this layer. While BIM is the apparent technology of choice during the design phase, the digital twin and CDE connect to the physical world throughout the project lifecycle.

The *"Digital Tools" layer* act as the mediating layer between the physical and data layers. This layer act as messengers transporting information between the data and the physical layers. Technologies corresponding to this layer include but are not limited to Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), Blockchain technologies, Big data analytics, AI, ML, Cloud-based project management technologies.

Finally, the *core data management layer* that manages core data functions of the project lifecycle from its cradle to grave. This layer is usually responsible for data security; privacy and ownership issues are typically abstracted from the physical layer. The importance of such a layer has become inevitable with the rapid developments being witnessed in the space of Construction 4.0 (Sawhney *et al.,* 2020).

3.1 Conceptual Framework

The layered model detailed above brings to fore the interactions between various technologies within and across the layers. The "world view" of construction 4.0 thus conceptualizes a continuous and complex network of interactions spanning all four layers. The roles and functions of the people involved are significantly altered with the advent of this new paradigm. New organizational roles have emerged and become central players in construction project execution across the project lifecycle. The people and technologies interact and facilitate information flow and exchange across the layers through defined processes. The current review adopts the established People-Process-Technology (PPT) framework to conceptualize and structure the interactions and components of the "world view" of Construction 4.0. Figure 2 illustrates the PPT framework for the various parts across the project lifecycle. For this review, the construction project lifecycle is divided into five phases: Design (including engineering), Documentation (including contracts), Construction, Operations & Maintenance, and Renovation/Demolition. As described in Figure 2, various technologies play a significant role in assisting people in multiple processes associated with the project lifecycle. Apart from the new technologies, the advent of Construction 4.0 has created new functions for people and new processes in the different project lifecycle phases.

The design phase transformed with the advent the core technologies such as BIM. The BIM modeler roles are becoming increasingly central to this phase to create collaborated and coordinated designs. The ideas of generative design processes, visualizations for coordination are becoming mainstream. Technologies ranging from Virtual Reality (VR) to Extended Reality (XR) are increasingly taking the aid of BIM and gaming technologies to make such visualizations and coordination possible among various stakeholders. AI/ML helps generative design go just beyond code-compliance and include complex sustainable goals, often involving multi-dimensional iterative analyses. Semantically enriched BIM models aid the documentation phase starting with automated regulation checks to reduce pre-construction permit times. Natural Language Processing (NLP) in creating Machine Intelligence (MI) help in interpreting contractual clauses and creating automatic payment mechanisms using Blockchain technologies. Such processes are increasingly redefining the roles and responsibilities of people involved, including the urban authorities.

The construction phase being the most cost and intensive stakeholder phase of the project, has witnessed a plethora of digital technologies aiding the phase. A distinction can be made here with the technologies incorporated into the constructed facility to help further phases of lifecycle to those technologies that help in construction. IoT-based devices and sensors belong to the first category predominantly. The IoT-based technologies are also increasingly being used in the latter category and specially to monitor equipment productivity. The capture of field activity using UAV and LIDAR-based photogrammetry is gaining momentum to monitor and control project activities. With the advent of BIM-CDE platforms, the induction of new roles to control, maintain and manage data is now becoming significant. The integration of schedule (termed 4D-) and cost (termed 5D-) based information into the data environments make informed project management possible. Integration with organizational ERP systems to achieve cost and payment management is also being witnessed. The use of cloud-based project management systems is increasingly being utilized due to the remote locations where construction projects are typically executed. The functionality of digital technologies now spans beyond the traditional cost-time-scope goals of construction project management. The use of technologies like RFID in construction safety and material management is a case in point. Such developments redefine the functions of PMC consultants, project managers, and even audit personnel to get updated to digital technology-enabled processes.

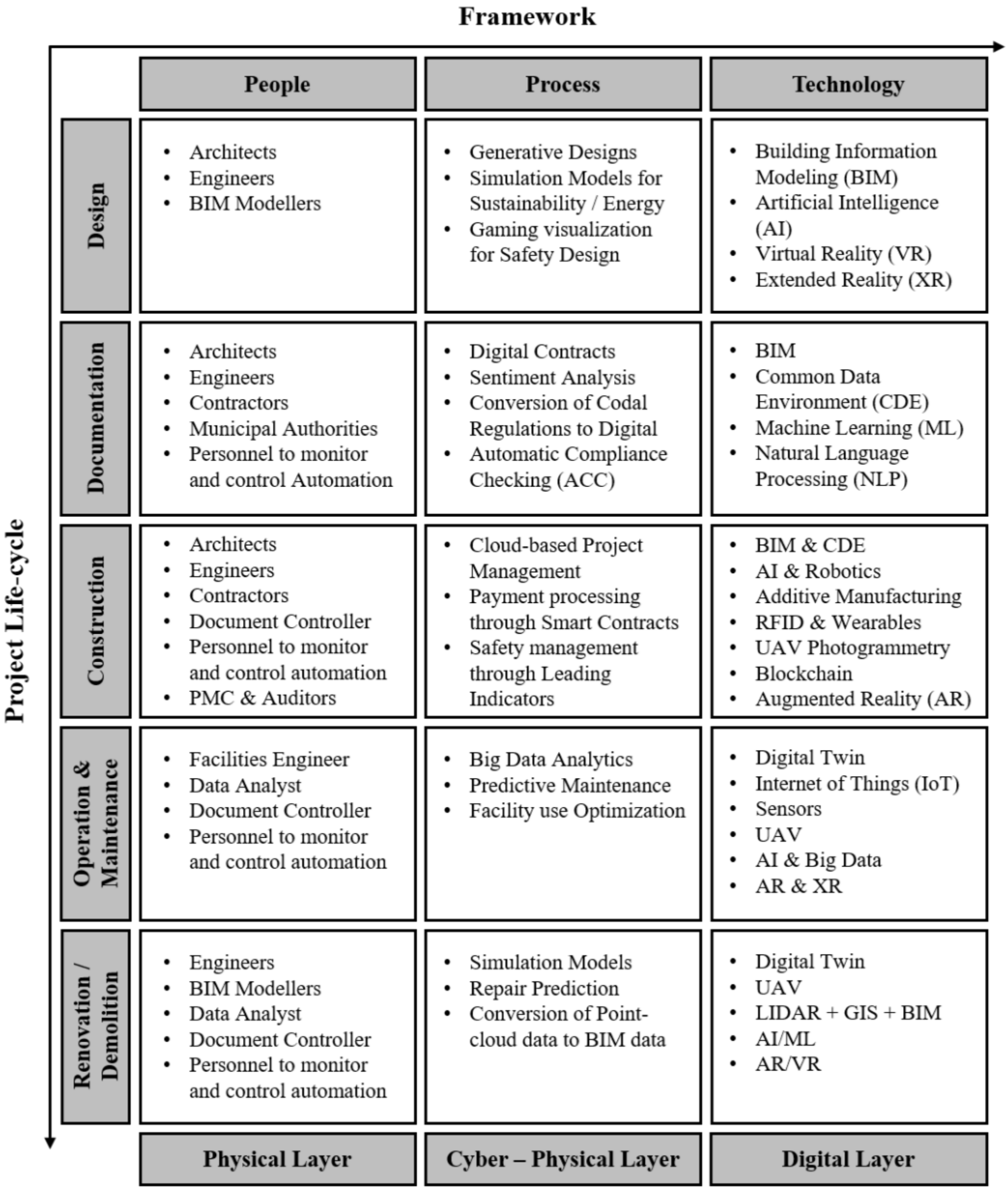

Fig. 2 The project lifecycle vs. people-processes-technology framework

Additive manufacturing or 3D printing, driven by BIM-CDE data, aid in the construction phase. Similarly, advanced construction robotics aid in translating the information from the data layer to the physical world.

Complex freeform geometries can be made possible through such technologies. Finally, blockchain-based technology can also be used in project management for automated payments based on ledger technology and digital currencies that can reduce the interruption in payments leading to project delays.

The role of data analysis and "big data" handling come to the fore in the operations and maintenance phase. The IoT-based sensor and allied technologies often lead to the generation of rich large datasets. Big data analytics play a significant role in the predictive maintenance of facilities. The concept of digital twin technologies extends the usefulness of digital technologies to this phase. However, such technologies also impose essential data requirements in the form of as-built BIM models to synchronize digital twin technologies to physical reality. Functional roles in such scenarios demand the personnel to be adept in technologies such as AR/MR to strategize and carry out repair and maintenance tasks. Finally, the advent of XR provides interactive means to visualization technologies.

The need for a synchronized digital layer to a physical layer becomes quite evident in the renovation/demolition phase. Many renovation projects where such layers do not exist now take the aid of advances in LIDAR, BIM integrated with Geographic Information Systems (GIS) to generate "as-existing" point cloud data. Analysis of such point clouds or BIM models developed from point clouds aid strategizing and visualizing renovation activities. AI/ML technologies find a place to assist in the analysis, while technologies such as AR/VR can help in the visualization functions in this project lifecycle phase.

As figure 2 illustrates, various technologies find function in different project lifecycle phases to advance the paradigm of Construction 4.0. In this process, various functional roles for people and processes to aid digitalization to become important. The extant research focuses explicitly on the advancement in the application of technologies in Construction 4.0. The following section details the progress in research on Construction 4.0 in the various phases of the project lifecycle.

4. STATE-OF-ART KNOWLEDGE ADVANCEMENTS IN CONSTRUCTION 4.0

Construction 4.0 is constantly evolving with the advances in research in the domain. The current section summarizes the current state of the art in the profession through the project lifecycle phases.

4.1 Design phase – Creation of the Digital World

The design phase transforms abstract ideas in the mental world of the owner/architect to digital models that can aid in construction. Digitalization of this project lifecycle phase originated with the advent of Computer-Aided Design (CAD) tools. The eighties have witnessed the emergence of CAD platforms for 2D drafting (Abanda *et al.*, 2015). This phase is now often referred to as BIM maturity Level Zero. At the turn of the century, 3D modeling started gaining momentum with the initial steps towards BIM as it is known now. In the 2010s, BIM had matured as a technology by incorporating libraries, national and international standards. During this stage, BIM evolved beyond the 3D modeling objective. BIM established the foundational platform for Building Lifecycle Management (BLM) with possible integration of Integrated Project Delivery (IPD). Steps towards universal adoption were laid with the evolution of open standards for Industrial Foundation Classes (IFC). Universal file formats such as IFC have a significant impact in developing BIM by enhancing interoperability (NBS, n.d.). BIM thus transformed into a collaborative platform to integrate information flows across manufacturers and designers. BIM thus helped in improving coordination among different design trades, including architecture, structural design, and other designers such as Mechanical Electrical and Plumbing (MEP) designers. BIM-enabled "clash detection" and "clash resolution" resulted in streamlining construction on site, thus saving cost and time (Sacks *et al.*, 2010). BIM has now emerged as the core platform for digitizing the construction industry (Chong, Lee and Wang, 2017). The key challenge lies in the integration of BIM through the project lifecycle. From a platform aiding design and cost management, BIM needs to evolve to become a fully integrated digital model (Gerrish *et al.*, 2017)

Object-oriented modeling (OOM) is the basic framework for BIM that considers the relationships and properties of the objects being modeled. Recent research studies in BIM lay the first steps towards semantic enrichment using the basic OOM framework. Semantic enrichment mimics human thought processes by utilizing existing information to analyse, predict, and draw new conclusions (Bloch and Sacks, 2018). However, attaining new facts through rule-inference does not translate to the full potential of AI/ML unless the model "learns" through problem-solving and decision making (Russell and Norvig, 1995). The steps in this direction are still in their infancy. Recent studies indicate the potential use of the vast accumulated data in the AECO industry that can be used to create datasets for machine learning algorithms to improve AI's performance (Bloch and Sacks, 2018).

The potential benefits associated with the design digitalization become evident if one considers the developments in Generative design (GD). GD was proposed to aid the creativity of humans as *"Interactive Evolutionary Systems"* (IES) (Bentley, 1999). The generative design principle is defined as a process of design exploration under constrained conditions driven by the designer and aided by the historical data of previous parametric designs (Krish, 2011). The framework for generative design has evolved from constraint-based parametric modeling to optimized design solutions, often utilizing advanced algorithms such as genetic algorithms (GA). Generative design can thus aid the architects by considering the previous design decisions under similar constraints. One such application of GD is to generate interior furniture layouts depending on rule-based compliance checking (Sydora and Stroulia, 2020). However, the configurations generated through GD are prone to subjectivity and can lead to aesthetic issues (Krish, 2011). Such challenges are expected to be tackled with the integration of AI & ML.

A natural extension to GD is BIM-based Simulation modeling to generate different scenarios to assist decision-making in design processes. For instance, BIM-aided building energy simulations help optimize energy consumption to design better sustainable buildings (Meža, Turk and Dolenc, 2014). Such studies consider multiple variables such as but not limited to wind speed, wall-window ratio, sun paths, building orientation to optimize the energy efficiency, thus reducing the electricity consumption to improve the green rating of a building (Samuelson *et al.*, 2016). GD is usually utilized to map the parameters according to previous decisions made in historical observations at a given location under controlled environments (Caldas, 2008).

The utility of such intelligent design models extends to other areas of construction project management. Rule-based automated compliance checking for building permits has increasingly utilized deep learning techniques such as Natural Language Processing (NLP) to convert the rules from building to machine-readable formats (Salama and El-Gohary, 2011). In safety design, the researchers have tried to analyze BIM-based models to integrate fall protection systems in the construction schedule to enhance site safety (Benjaoran and Bhokha, 2010). Studies have also attempted to design such controls through rule-based algorithms driven from OHSA guidelines (Zhang *et al.*, 2013). However, key barriers and challenges in such applications rest in the reliability and interoperability of the BIM-based data transfer. Further, disagreement and ambiguity on rule interpretation by the machine-aided systems may lead to complex disputes.

One crucial dimension is to transform the digital models to be amenable to construction processes. To this end, the integration of time (4D-BIM) and cost (5D-BIM) related information on common platforms is essential. Increasingly, cloud-based storage, access, and computing are being utilized to integrate such services, including databases, networking, server, storage, software, or even analytics. Cloud-based computing offers flexible resources, scalability, and easy accessibility to data through the secure protection layer. Such initial concepts transform to the formulation of Common Data Environments (CDE). CDE is defined as the data environment based on extensive data gathered from smart equipment and humans on the field and stored in a shared space to aid in decision making and by both humans and other machines (Kling and Turk, 2019). The creation of CDE enhances the management control over a project by increasing quality, reducing delay and cost. However, key challenges remain in standardized data exchange formats, the structure and nature of information required in realizing construction (Radl and Kaiser, 2019).

Finally, the phase also witnessed the application of smart-contracting regimes. In the case of contracts and Documentation, Natural Language Processing (NLP) based deep learning techniques are now being explored to classify the types of contract clauses and understand how the clauses impact the dispute generation in projects. Such tools in the pre-construction stage help contractors in the decision-king process (Agrawal, Jagannathan and Delhi, 2021). In the case of smart contracts, NLP can be used to convert conventional contracts to digital contracts. With the help of blockchain technology, the transactions can be automated through the web of self-executable and self-enforceable payments (Mason, 2017).

4.2 Translation of Ideas from Design to Physical World

Research in Construction 4.0 is now witnessing the application of technologies that aid in understanding the design detail and its translation to physical spaces. Augmented and Virtual realities (AR/VR) are computer-simulated scenarios where the user has continuous interaction between the mixed or virtual reality (Gavish *et al.*, 2015). In the case of virtual reality, the user experiences an alternate reality by being immersed in it. Significant challenges lie in the initial investment of VR technologies and the user's cognitive conflict between vision and perception (Berg and Vance, 2017). On the other hand, the use of mixed reality or AR addresses such challenges. AR integrates the virtual objects in the natural environment. AR tools now rely on tracker-based technologies to identify the location through Global Positioning Systems (GPS), thus populating the virtual data objects in their accurate places (Koch *et al.*, 2014). The use of AR/VR systems in construction planning has been demonstrated in recent research studies. For instance, in site-layout planning, marker-based AR technology was utilized to visualize and locate the temporary facilities at optimal locations (Singh and Delhi, 2018). AR has also been applied in the facility management domain to identify potential problems in building service lines hidden behind the false ceilings (Liu and Seipel, 2018; El Ammari and Hammad, 2019). It is now understood that AR prevents the problems of cyber-sickness problems often associated with VR. However, in the construction domain, challenges remain in developing virtual environments and accurate positioning to generate immersive, realistic visualizations (Rebenitsch and Owen, 2016).

Mixed reality (MR) offers advantages of both AR and VR. MR is an extended AR, where the user can interact with the virtual objects and get a better immersive experience. Extended-reality or X-Reality (XR) is an umbrella technology utilizing all the VR, AR, and MR capabilities to combine real and virtual world experience (Alizadehsalehi, Hadavi and Huang, 2020). XR is initially conceptualized in the 1990s' through computerized displays on eyeglasses. XR technology was often referred to as cross-reality by the researchers (Coleman, 2009). The demonstrative use of XR is now evident in digital architectural design applications, where both spatial immersion and emotional immersion are taken into considerations for better collaborative and efficient outputs (Stals and Caldas, 2020).

MR has shown its potential in transforming human behavior on construction through safety training in the form of serious gaming(Guo *et al.*, 2012). In this BIM-based gaming manifestation of construction sites, the personnel trains in the virtual world on simulated real-life scenarios. This method helps in understanding and identifying the safety hazards due to ignorance or inadequate precautions. Similarly, optimal travel path identifications were also demonstrated utilizing such platforms to visualize the accessibility and conflict between tractor-trailer movement at a construction site (Lin *et al.*, 2013). Often, these platforms are combined with simulations backed by multi-objective optimization algorithms to achieve desired objectives (Singh, Patil and Delhi, 2019).

4.3 Project Execution – Interactions in Physical World

Empowerment of machines and systems to show near human or human-level intelligence in specific areas is often referred to as Artificial Intelligence (AI) (R. Li *et al.*, 2017). One significant feature of Construction 4.0 is the application of AI in varied areas. AI is employed in pattern recognition and image processing for safety compliance in the areas of protective equipment (J. Li *et al.*, 2017). AI has also demonstrated its applicability in the automatic sequencing of construction projects by integrating geometric and material data combined with scheduling rules (Liu, Al-Hussein and Lu, 2015)**.** AI, often combined with optimization models and rule engines in constrained environments, is utilized to produce a feasible construction schedule (Kim *et al.*, 2013). The challenges in integrating AI in construction remain in modeling and applying appropriate machine learning algorithms utilizing accurate case-specific data (Bloch and Sacks, 2018). It is also observed, the inherent probabilistic base of such technologies fails to generate perfect decisions (Lu *et al.*, 2018).

The key technology in implementing Construction 4.0 in the physical world relates to the Internet of Things (IoT) (Adat and Gupta, 2018). IoT can be described as a global network where machines (often termed as smart objects) can communicate with each other share information to attain a common goal (Lee and Lee, 2015). With the increased data speed of wireless networks and the decrease in the congestion in internet networks, the capability of IoT has enhanced to process real-time data. For these reasons, the industry has also recognized IoT as the "technology of tomorrow" (Ng and Wakenshaw, 2017). Cloud-based IoT to enable prefabricated construction has demonstrated its utility in enhancing collaborative project delivery across stakeholders (Xu *et al.*, 2018). IoT offers key technology to mediate information between the physical and data worlds (refer to Figure 1). However, the challenge of using IoT across the horizontally fragmented industry lies in the ownership and security of the data generated.

Apart from data generation and transformation, the physical world's key technologies aim to translate digital models to physical models. Two technologies, namely robotics and additive manufacturing, aim to automate the above function. The utility of robotics in construction in being explored since the 1980s. Robots are employed for precision and the ability to reach areas otherwise difficult for humans (Kehoe *et al.*, 2015). The use of robotics in specific construction tasks such as masonry blockwork and steel assembly is demonstrated (García *et al.*, 2020).

Similarly, Automated unmanned aerial vehicles (UAV), often referred to as drones, are employed for inspection, monitoring, and coordination at construction sites (Bryson and Winfield, 2017). Even with the demonstrated capabilities, the mainstreaming of robotics in construction still faces critical challenges in operational safety and logistics management (Buchli *et al.*, 2018). Here the project nature of the construction industry, a key difference from the manufacturing industry, comes to the fore. The project nature implies frequent mobilization and de-mobilization requirements of the robots and added uncertainties of working in novel environments as opposed to fixed locations of the manufacturing sector. Such challenges often consist of crucial barriers to adoption.

Additive manufacturing, often referred to as 3D printing, is the second technology that automates designs to real-life structures. From its advent in 1980, additive manufacturing benefited from innovative printing techniques and utilizing novel materials (Weller, Kleer and Piller, 2015). By the turn of this century, the affordability of 3D printing technologies has improved and continues to improve even now (Forcael *et al.*, 2020). There is a divided opinion on the applicability of 3D printing technologies in Construction 4.0, especially with materials such as concrete. Research and advancements in the material domain with innovations in novel materials with favorable rheological properties indicate a promising future for adopting such technologies in the next few decades (Jiang, Kleer and Piller, 2017). Further, the availability of commercial 3D printers for large-scale applications remains a key challenge (Wu, Wang and Wang, 2016). Despite such challenges and the infancy of applying this technology to construction, additive manufacturing offers immense potential in waste reduction, precision construction, and enhanced safety benefits. Thus, this domain remains a potential research domain in Construction 4.0 across the world.

4.4 Project Monitoring and Control

The Project Monitoring and Control phase immensely benefited from the technologies of Construction 4.0. Several studies focus on this aspect for the demonstration of the utility of various technologies. IoT technologies are utilized in monitoring construction equipment productivity as well as safety compliance monitoring. The use of RFID and wireless wearable sensors have helped reduce accidents and casualties on construction sites. RFIDs generate an electromagnetic field that exchanges information and notifies the safety professional of potential safety violations (Lu, Huang and Li, 2011; You and Feng, 2020). Further, IoT is also used in supply chain monitoring to track material right from supply points through its transit to stockyards until it is absorbed in the construction process (McNamara and Sepasgozar, 2018). Thus, the data of material flow aquired can help optimize and streamlining material flows in construction, avoiding process delays and reducing material wastage.

Construction progress monitoring is one key area where rapid strides were made in implementing construction 4.0. LIDAR proves extremely useful in this area where the topography or geospatial information is collected on objects present at the site in the form of point clouds. LIDAR was demonstrated successfully to acquire timely information on the progression of construction. Further, it was also shown to capture a detailed record of the construction process, which can be inquired later. The application of LIDAR technologies particularly proves helpful on transportation infrastructure projects predominantly linear in nature (Puri and Turkan, 2020). LIDAR integrated BIM models are used to check deviation of actual construction from the planned digital models. Thus, LIDAR plays an essential role in quality monitoring on construction projects (Wang *et al.*, 2015). An allied technology in UAV-based photogrammetry is also increasingly being used to generate actual site data by capturing high-quality overlapping images of the construction project. These high-definition images are overlaid with 4D BIM models to check for deviations between "as-planned" schedules to that of as-built ones (Kim, Kim and Kim, 2013). Cloud-based BIM enables Real-time progress monitoring of projects at construction sites, which offers utility to site supervisors to update various construction activities. Studies have illustrated frameworks to use such data at a head-office level to track progress through techniques like earned value analysis (Matthews *et al.*, 2015).

4.5 Project Documentation – from Physical World to Digital World

As the execution of a construction project proceeds, there is a critical need to document and store all the relevant information on a common platform, accessible during the maintenance phase until the structure's end of life. Digital twin (DT) technologies help address this need. Digital twin technology can be defined as an exact digital representation of the construction facility data synchronized with the physical world throughout the project lifecycle. A DT should consist of all the information from the design phase and get updated through accurate data capture during the construction phase. The DT should continue to serve as a source of reliable information through the operations maintenance and renovation phase. There are some critical differences between the DT and the BIM technologies as already established (Mateev, 2020).

While BIM is predominantly used in the design and construction phase, digital twins work on real-time and operational data. Essentially, BIM models transform into digital twins as we proceed toward operations. The utility of digital twins is further enhanced by the potential to be aggregated to urban-level digital twins that can be used for urban level analysis and disaster resilience studies. Such utility translates to value additions throughout the constructed asset's lifecycle. Also, while BIM focuses on developing systems for the built environment, the digital twin technologies consider the interaction of people with the built environment. As-built BIM usually contains the data regarding geometric and parametric information of the systems involved in the constructed asset. Thus, DT technologies can be considered a superset to BIM technologies, setting direction for the construction industry. Often, the integration of BIM and CDE form the core foundational basis for digital twin implementations

The updated and synchronized digital twins suit is ideal for the operations phase for the facilities management (Lin *et al.*, 2018). Researchers have also used a parametric template-based approach to replicate the survey data aquired from site through LIDAR and photogrammetry on a lesser scale than that of digital twins. Rule-based algorithms were used to identify the location, proportion of elements, and mapping of the ingredients in the BIM environment. The generated output is then iteratively modified by the user to achieve the best results through these semi-automatic systems (Dore and Murphy, 2014). For buildings that are already existing, Airbourne LIDAR data is used to automatically create the building footprints, which can be used for 3D visualization in GIS. This footprint data also caters to estimating urban heat islands and flood insurance (Zhang, Yan and Chen, 2006).

One crucial aspect in the project documentation relates to the sanctity and security of the data acquisition and model updating processes. Significant challenges lay throughout the project lifecycle owing to the involvement of multiple stakeholders. Native BIM format-based data sharing attracts data losses and vulnerabilities associated with unintended modifications. Disputes arise over the ownership of the model and for any loss of data encountered. The technologies such as OpenBIM formats facilitate data sharing across project stakeholders with appropriate view/edit permissions. The use of data transfer formats like IFC supports such information exchange for enhanced collaboration in different project stages (Juan and Zheng, 2014). However, the challenges remain in standardization, interoperability, data interdependency, and data security, such as authentication and role-based user entitlements (Afsari, Eastman and Shelden, 2016).

4.6 Facilities Management

As per the researchers, IoT will have a broader impact in the facilities management phase. The use of IoT is often mandatory to achieve the concept of a smart city that requires handling a large amount of data to maintain the public facilities (Zanella *et al.*, 2014). Low-cost sensoring nodes are used as sources for gathering data, such as smart bricks. Such smart bricks are distributed at prespecified locations to collect data in high spatial density (Engel *et al.*, 2004). However, the challenges in IoT adaptation relate to data privacy and security. Also, the vast amounts of data generated from the smart objects bring to the fore the utility or redundancy of such data in analysis models (Mohamad Noor and Hassan, 2019). Thus, the facility management in Construction 4.0 relates to "Big Data Analytics," which usually refers to a large amount of data that needs to be stored, analyzed, and processed considering the outburst of heterogeneous data generated from multiple technologies (Gandomi and Haider, 2015). The data may consist of images, texts, videos, sounds, geometries, or a combination of them (Assunção *et al.*, 2015). The management and analysis of Big Data form the fundamental concern in urban planning and management, especially in the areas related to smart cities (Osman, 2019). Big data analytics find use in predictive maintenance of assets, optimization of asset operations. Often, IoT technologies act as the source to the generation of such heterogeneous Big Data (ur Rehman *et al.*, 2019). However, critical challenges for big data remain in terms of internet connectivity, cost of implementation, data privacy, and security (Bilal *et al.*, 2016).

A key aspect of facilities management is the sanctity of the digital data layer to that of the physical layer. Such synchronization of the digital and physical world is achieved through controlled feedbacks, optimization, and interactions between the digital twin model and the constructed asset (Deng, Menassa and Kamat, 2021). Several researchers have proposed different frameworks to implement digital twins in the construction 4.0 paradigm. For instance, a serious game-based approach was proposed for city-level digital twins (Mohammadi and Taylor, 2019). Similarly, systematic frameworks to integrate different heterogeneous data sources were explored (Lu *et al.*, 2020).

Finally, synchronization is also aided by AR-based mapping of services on the 3D environment where these are not readily visible (Liu and Seipel, 2018).

4.7 Repair and Rehabilitation

Proactive maintenance has become a crucial factor in controlling the global expense in the repair and rehabilitation of existing projects. Proactive maintenance can be classified into three strategies: preventive maintenance, predictive maintenance, and improvement maintenance. Preventative maintenance is about local repairs and replacements that reduce any non-planned activity or break-down. Predictive maintenance is the cyclic inspection of elements to decide on the following maintenance action depending on the degradation level of the component. On the other hand, improvement maintenance or rehabilitation is required when an element performs under its pre-established service level (Flores-Colen and Brito, 2010). The impact of scheduled proactive maintenance was highlighted by (Che-Ani and Ali, 2019) in a case study over hospital support services. Research over a multifamily occupied building has shown that almost 38% increase in the energy cost is due to degradation of the building components such as roof, facade, and window that are not proactively maintained (Farahani, Wallbaum and Dalenbäck, 2019).

The strong impact of IoT can also be visualized in renovation projects. The IoT-based smart windows are installed in the building to be renovated to understand the user behavior under different conditions such a humidity, illumination, temperature, etc. The generated data is analyzed through a decision tree-based ML algorithm to decide on the best design parameters during the renovation stage (S. Rinaldi *et al.*, 2020; Stefano Rinaldi *et al.*, 2020). ML is also employed in studies to optimize the overall energy consumption during the renovation stage (Seyed Amirhosain Sharif, 2020). In rehabilitation sequencing, an event-based approach was implemented to investigate the optimal timing for municipal water mains. This model demonstrates the trade-off between budget constraints in rehabilitation and increased operational cost due to leakages, breakages, and energy consumption of unimproved pipes (Roshani and Filion, 2014).

For existing or heritage structures that need rehabilitation or renovation, detailed simulations are often employed on various aspects related to repair and restoration. To this end, LIDAR is often used to scan the existing building to generate detailed point clouds. These point clouds are then overlaid to create BIM models. The creation of BIM objects from the point cloud often involves considerable manual effort and remains a critical bottleneck. Researcher in this direction has demonstrated the application of ML to classify construction objects such as beams, columns, and walls, by considering the spatial relationships and geometric features of the point-cloud data (Xiong *et al.*, 2013). LIDAR-based city-level point cloud data is also analyzed based on GIS and unsupervised learning to create clusters of types of objects in a city. Such studies establish the need to develop a database for digital twin models in existing cities to convert them into smart cities (Xue *et al.*, 2020).

4.8 Demolition and Recycling

The method of demolition of an existing structure through explosives in a controlled manner is preferred over other techniques due to its speed of execution and low-cost impact. There are many instances of controlled demolition on structures like bridges, towers, silos, and chimneys. However, due to the complex geometries of the existing structures, it is often challenging to control buildings' collapse in a pre-determined footprint. Controlled demolition of the buildings requires the design for the amount of charge, charge locations, blasting sequence, and the delay interval. The optimum design of the same can be achieved through simulation of the finite element model over a set of hyperparameters (TAVŞAN, GÜRBÜZ and TÜRKER, 2021). BIM-based models can be used to simulate the failure modes and in managing demolition sequencing.

The accumulation of high amounts of construction and demolition wastes (C&DW) is a cause of concern. The C&DW domain has received significant attention from researchers. Looking at the possibility of achieving a circular economy and reducing the carbon footprint of construction materials, recycling of C&DW has become an area of focus. For instance, the presence of C&DW in a given area was estimated with the aid of the google earth engine and the application of ML algorithms to a high degree of accuracy (Zhou *et al.*, 2021). When the C&DW are at a recycling site, a significant challenge pertains to the classification of different categories of waste. The researchers have addressed this problem through image processing (Anding *et al.*, 2011) and infrared spectrum (Kuritcyn *et al.*, 2015) methods in a supervised learning setup. In smart city designs, the framework for identifying and processing potential C&DW is given by (Sartipi, 2020). This framework proposes an IoT network-based identification of the construction materials to keep track of the number of times a particular element has been recycled. Further, the framework suggests the transport of wastes through automated dump trucks, where the segregation is done by supervised machine learning. BIM can also be used in the planning strategies for C&DW management. The strategies comprise reducing, reusing, recycling, and landfilling. The process map (Won and Cheng, 2017) and the framework (Gupta, Jha and Vyas, 2020) proposed by researchers for BIM-based C&DW management illustrate the usefulness of such technologies.

The discussion over the advancements in different construction project phases can be tied to the essence of information creation and the flow in the cyber-physical environment. Figure 3 summarizes the information flow across the different layers and between technologies as evident in the Construction 4.0 paradigm. As can be witnessed from the figure, the project lifecycle is characterized by complex and intense information flow through the project lifecycle phases. The advent of digital technologies is substituting the human interventions required in data collection, modeling, and processing. While certain digital technologies predominantly operate in specific layers leading to the creation or transformation of information, other technologies aid in transporting information across layers. While some technologies are majorly associated with digital world creation, the different technologies take such information and process the data to aid decision making. The data processing layer performs this same function to analyze vast amounts of data generated in the physical world and translated to the digital world. Such meta layers are highly crucial in imparting the desired intelligence into the Construction 4.0 implementations. Finally, the relevance of the overarching data management layer involving data security and privacy is now understood.

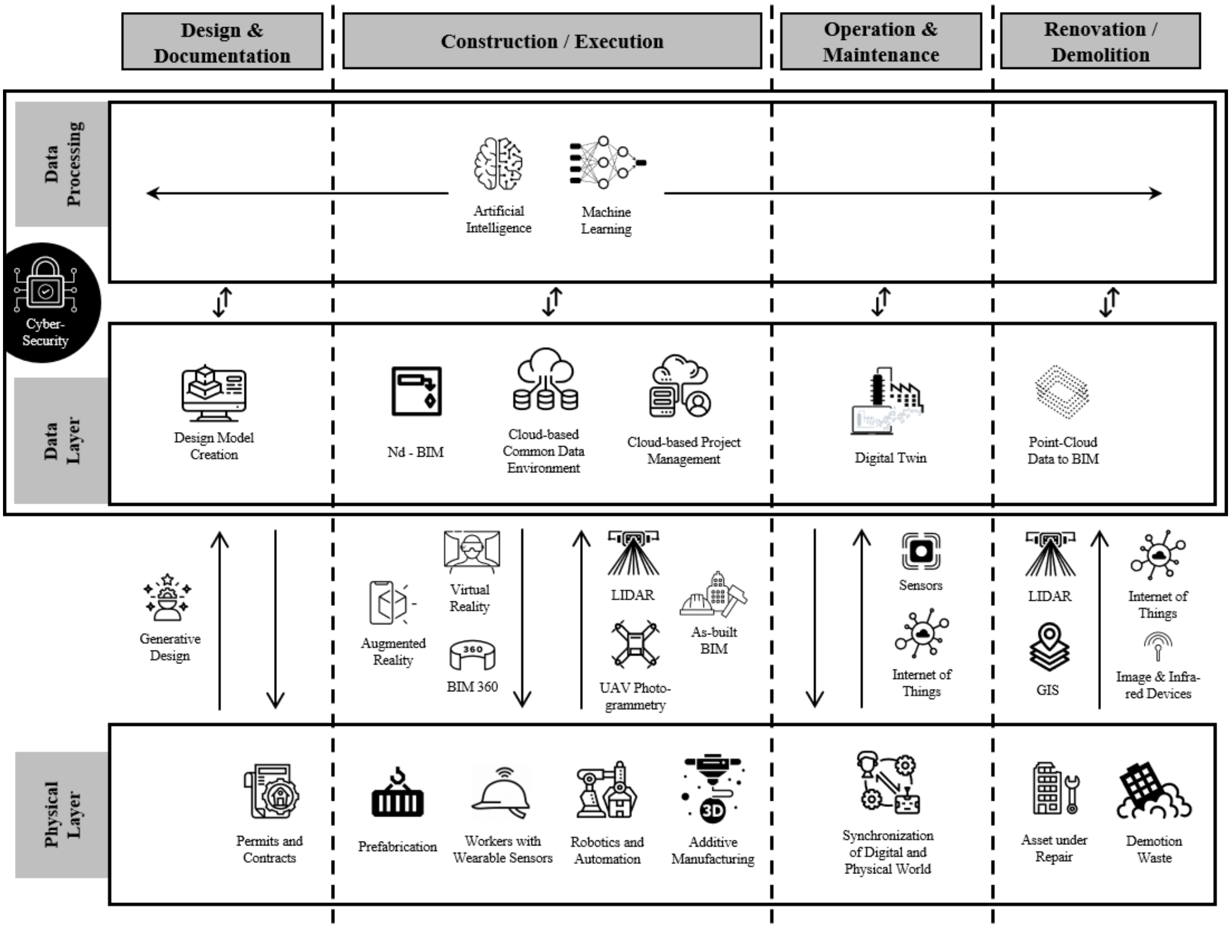

FIG. 2: Information flows through different project lifecycle phases illustrating intra- and inter-layer interactions

5. CHALLENGES ASSOCIATED WITH OUR KNOWLEDGE AND PRACTICE

Though construction 4.0 has shown potential benefits, significant challenges lay in its implementation and mainstreaming in the construction industry. Prolonged intermediate hybrid construction scenarios are inevitable before the industry fully adopts digitization (Winfield, 2020). The research studies have demonstrated the usefulness and relevance of different technological advancements. However, much of the work in Construction 4.0 remains at a proof-of-concept stage with capability demonstration by various studies. However, a gap is evident between realizing and commercializing such concepts (Maskuriy *et al.*, 2019). Even though the stakeholders are willing to adopt the technologies, the high initial investment cost often proves detrimental to transformation (Osunsanmi *et al.*, 2020). The return of investment period for the technologies involved is extended compared to project durations. Thus, the returns are realized over multiple projects for any given organization. Hence, research on a systematic and strategic plan in technology implementation and adoption is crucial (Muñoz-La Rivera *et al.*, 2021). The innovations, especially in robotics and additive manufacturing, are often associated with loss of livelihood to construction workers. The sensitization of the labour force to ready them to this new construction paradigm is thus a key challenge. The transformation often couples with changed organizational roles and responsibilities of the employees with more unique skillsets. The advancements of digital technologies present unprecedented opportunities for newer job roles, including the possibility of bringing in much-needed gender diversity in the often male-dominated construction industry (García de Soto *et al.*, 2019; Winfield, 2020). Construction 4.0 demands a more coordinated and collaborative approach which might be a challenge in a highly fragmented industry like the construction sector. As the construction industry is recognized as the one with low collaboration, communication, and coordination vertically or even horizontally, the adaptation of project delivery paradigms such as IPD becomes inevitable to facilitate Construction 4.0 (García de Soto *et al.*, 2019; Lekan *et al.*, 2020).

From the technological perspective of construction 4.0, one key challenge is data security and data protection. With the high availability of data generated from multiple sources, the threat remains in exploiting this confidential data (Kling and Turk, 2019). There remain critical challenges in terms of data security, data sanctity, and data ownership. The utility of blockchain-based technologies to ensure control and security is proposed (Lokshina, Greguš and Thomas, 2019). Another critical challenge is associated with the need for proper contracting regimes to support Construction 4.0. Due to the dynamic nature of the interaction between construction 4.0 technologies, contracting methods are not standardized in practice. This standardization is also driven and government policy directions and initiatives. Construction 4.0 cannot be realistically achieved without such standardization. The initial steps in the direction of standardization are achieved through the implementation of ISO-19650. However, further steps are necessary to implement supporting standards to realize Construction 4.0 (Winfield, 2020). Finally, one of the vital growth indicators for an industrial sector is the presence of peer networks for information, benchmarking, and feedback. The same is valid for adaptation of construction 4.0 as well, where there is an imminent organic need for the development of such peer networks (Sawhney *et al.*, 2020). However, construction 4.0 still lacks from having such knowledge networks currently

6. CONSTRUCTION 4.0 IN INDIA

The digital transformation has gained momentum worldwide in the last decade. Construction projects across the world are increasingly adopting digital technologies for various functions and operations. Two different approaches are driving the digital transformation of the industry. The first is the grass-roots adoption of construction 4.0 in the industry based on the value proposition offered by various technologies. Second is the top-down policy-driven and mandated transformation of imposed use of digital technologies. Both the approaches have their own merits. The grass-roots adoption provides an organic evolution of the industry with firm establishment and acceptance of the technologies. However, many such technologies have advantages where the returns on investment are realized over a long period compared to the project construction phases. The fragmentation of the construction industry across the lifecycle phases further complicates the grass-roots adoption. Thus, the top-down mandates may also play a crucial role in providing the initial impetus towards the transformation. Globally, there were some critical drivers in the direction. An example case is the adoption of BS-1192 in the UK towards the adoption of BIM in construction. Similarly, the creation of the international standard ISO-19650 in 2018 is significant in this direction. Such standards provide frameworks to aid the transformation of the industry and help the policymakers draft policies according to the global standards. In India, the transformation is predominantly characterized by grass-roots adoption. While the Indian construction industry clearly understands the benefits and the inevitability of the digital transformation, the transformation across the lifecycle realizing the benefits to the owner and the user of the projects is yet to gain momentum. In a country such as India, specific challenges exist in terms of skilled human resources, process frameworks. Incentive mechanisms for stakeholders and integration across the lifecycle to adopt and use digital technologies. Some key initiatives were getting started in this direction by revising the current standards to support the transformation. A synergetic top-down policy mandate with sustained momentum from grass-root adoption might benefit the digital transformation in the country.

7. WAYS FORWARD

The enormous possibilities extended by construction 4.0 to researchers is academically motivating. The promise of huge benefits of construction 4.0 in almost every area of project management includes time-saving, cost-saving, improvement in quality and collaboration, enhancement of safety, and Sustainability (Oesterreich and Teuteberg, 2016). However, with the considerable amount of research in the area, our combined knowledge in this area needs substantial augmentation. The full potential of construction 4.0 can only be realized with dedicated rigors and inter-disciplinary research in this field. In data science, AI and ML need to be further explored for their utility in data processing and predictive modeling.

Similarly, studies may focus on the optimal and efficient use of IoT to ensure the timely availability of rich, detailed data. Even though technologies like additive manufacturing and robotics are in use in construction, the extent of their use and adaptation of the same across the industry needs to be enhanced, focusing on execution in remote areas and areas where humans find it difficult to access. The utility of using immersive technologies like AR/VR/MR and XR for efficient and collaborative decision-making needs to be explored. Combining such visualization technologies with serious gaming might create advancements in the ways we train construction personnel for safety and other allied areas. The challenges detailed earlier also indicate the need for future research focussing on the strategic involvement of people along with appropriate contracting structures under favorable policy regimes. Research at the levels of organization, sector, national and global levels is needed. Finally, construction 4.0 would be incomplete without integrating the social sphere, the environmental concerns, and the sustainability aspects.

8. CONCLUSIONS

The fundamental design principles of construction 4.0 are information transparency, decentralized decision making, seamless information flow, technical assistance through robotics and automation, and interconnectivity and interoperability among these applied technologies (Hossain and Nadeem, 2019). In this paper, the possibility of these design principles aligned to construction project management is discussed through the people, process, and technology framework. The framework is applied across the project lifecycle to conceptualize the interaction among the physical and digital world through the cyber-physical layered model of Construction 4.0. In comparison to its counterpart, Industry 4.0, it can be understood that the adaptation of technologies and innovative processes is relatively slow in the construction industry (Zabidin, Belayutham and Ibrahim, 2020). Understanding the interaction among these technologies and the current research trends becomes important in deciphering our upcoming future. The construction 4.0 research is still in its infancy, leaving scholars and practitioners an open ground for exploration.

Significant progress has been made in the technologies associated with Construction 4.0. However, specific vital challenges remain that need to be addressed to facilitate the mainstreaming of digitalization. Globally, such challenges include but not limited to the alignment of incentive mechanisms of various stakeholders, skilling and training of personnel to accept the technologies, project lifecycle integration in a fragmented industry, specific process-related changes to facilitate digital technologies, and policy frameworks to enable digital data security and integrity for the projects. Therefore, such challenges span the technology, social, economic, and policy spheres. Synergetic approaches to encourage industry-wide adoption combined with conducive contractual frameworks and digital-ready processes with skilled teams are crucial in achieving the benefits exhibited by the technological advancements in this space. Thus, there is a significant need for further research in the areas to understand better the interaction between various technologies and the dynamics of implementation in other spheres. With the development of methodological and technological frameworks, we look forward to the industry's rapid growth and adoption of construction 4.0.

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