Cyber-Physical Systems: Matching Up its Application in the Construction industry and other Selected Industries

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Abstract

Optimization of the delivery processes of different facets of human dwelling has been enhanced by technological innovations in recent times. One of such is the application of Cyber-physical systems (CPSs). This has been widely applied to different fields of human endeavors and the benefits accrued from such applications are quite enormous. The construction industry has been noted to be on the back foot of adopting such innovations despite the overwhelming usefulness. This study assessed the application of CPSs in the construction industry and having a comparative review with the application with other selected industries aided by the review of literature. Its potential benefits in different industries were discussed, and measures for its adoption in the construction industry were highlighted.

Keywords

Cyber-physical systems, Construction Industry, Applications, Other Industries

1.0 Introduction

Cyber physical systems (CPS) can be referred to as mechanisms that function on the premise of the integration of computation and physical processes. It is deployed with the monitoring of computer-based algorithms fused with the internet. It serves as the link between physical and virtual world. Some scholars have referred to it as 'realization technology' (Kim and Kumar, 2013). As described by National Science Foundation (2013), 'CPS are systems where physical and software components are deeply intertwined, each operating on different spatial and temporal scales, exhibiting multiple and distinct behavioral modalities, and interacting with each other in a myriad of ways that change with context'. Adaptation, intelligence and responsiveness are attained through the shared knowledge and information between the physical process and the computational decision components of CPS (Leitao *et al*., 2015). This is achieved with the embedment of computers and network monitors which ultimately control the physical processes, with feedback loops where physical processes affect computations and vice versa. More often, the cyber and physical components of such systems are independently built.

The working process of CPSs is often taken as that of embedded systems, however, there is a clear distinction between both systems. In CPSs, there is a large percentage of the physical component when compared with embedded systems (Wu and Li, 2011). Also, the computational element is the main focus in embedded systems whereas the nexus between the physical and computational components is significant in CPSs. The network of interaction between input and output is a core feature of CPSs unlike embedded systems which are more of standalone devices.

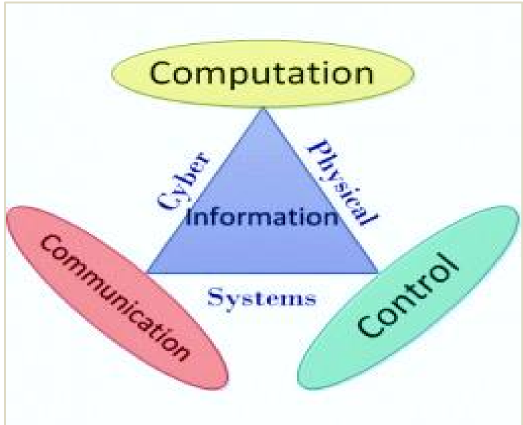

Figure 1: Cyber-Physical Systems Structure

CPS is widely applied in various fields of human endeavor. Efforts have been made to steer up its application in different aspects of human life. One of such is CyPhERS ("Cyber-Physical European Roadmap and Strategy") (Cerngarle *et al*., 2013). The European Commission under its 7th framework programme targeted at fusing and expanding the capabilities of the continent's integration and mobile computing and also placing it in firm grip of networked embedded systems. The ultimate objective is to build a regional strategic research and innovation driven by cyber-physical systems to secure the continent's competitiveness in this emerging field. Equally, the US government through the National Science Foundation bankrolled a research driven programme on CPS to the tune of $150 million, thereby putting CPS at the top of preference list for federal research investment; also countries like Korea, Japan and China have steered up research projects to help place CPS on the map of technological innovations (Kim and Kumar, 2013; Wang *et al*., 2012). This serves as a pointer with regards to the prominence of the application of CPS not just to human dwelling but also to its immense potential benefits to be accrued from a regional and by extension, global point of stance.

In view of the applicability of CPSs to different fields, this study presents the key features of CPSs; examine its application in selected fields and matching it up with that of the construction industry through theoretical lenses with the aid of reviewed literature; Also, highlighting the key benefits from its application to the selected fields under the study.

2.0 Key features of CPSs

According to Miclea and Sanislav (2011) some of the defining features of CPSs are physical component cyber capability; high level of automation; multiple scale networking; spatial and temporal integration at multiple scales and re-assembling dynamics. Wang *et al*., (2012) outlined the architecture of a CPS into four different layers. These are service implementation, service abstraction, business process, application layers. Service implementation layer serves as the foundation of the architecture. It entails sub units like communication unit, sense-actuate unit and computation-control unit. The physical world is monitored by the sense unit which then transfers monitoring information through communication unit to the computation unit. Instructions are given via control unit to actuate unit for physical process control. Sense-actuate unit is made up of sensors, actuators coupled with terminal computation module. The sensors observe the physical processes, while the actuators control the processes. The rules of actuators and storage capacity of real time data makes up the terminal computation module. Communication unit serves as communication mechanism by deploying 3G, 4G etc. Computation-control unit is made up of both computation and control units. Computation unit fuses discrete and continuous domains while control unit executes the management of time and space of the system.

The service abstraction layer simply outlines service functions gotten outwardly; however implementation details are not contained therein. This layer of CPS architecture also deals with description of interfaces' features, quality of service and operations usability. The third layer, business layer entails a couple of business processes that consists of CPS conforming to regular rules. Furthermore, it involves service composition, service collaboration, service substitution and space-time constraints. The various industry applications comprising of business processes makes up the application layer. This layer focuses on the integration of various application demands by fusing business models and professional understanding of different fields. This spans from vehicular systems and transportation, medical and health care systems, smart homes and buildings, social network and gaming, scheduling, power/thermal management, cloud computing and data centers, power grid or power systems, networking systems, surveillance, industrial process control, aerospace and air-traffic management, search engines, environmental monitoring, civil engineering, video processing, water distribution, robotics.

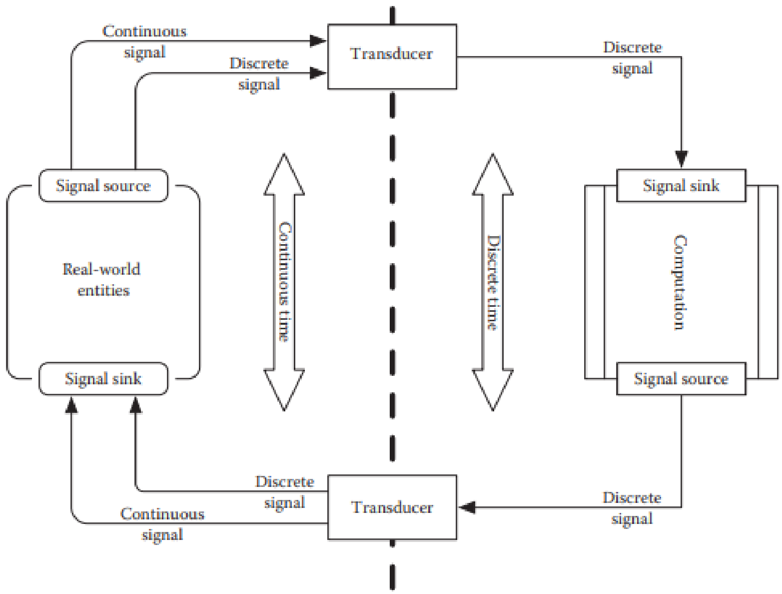

Figure 2: Basic Elements Cyber-Physical Systems (Knight *el al*., 2017)

From the highlighted figure, CPS basically has two distinctive working modes and these are the continuous function and the discrete function. Knight *el al*., (2017) describes this interwoven role in CPS as a simple two state "on" and "off" functions. Further stating that 'discrete functions arise in the real world with switches, but many signals in the real world that are intended to change the state of the logic function are continuous. Signals to which the logic function might react, and the signals that it generates, are discrete'. Discrete signals are produced that infuses the logic functions by transducer process which repeatedly signals in the realm of affairs. A vital element that distinguishes between discrete and continuous functions is time.

3.0 Application of CPS

The revolutionary impacts of CPSs have been felt in different spheres of human living. Its application is highly deployed areas like medicals and healthcare, construction, smart buildings and cities, automobiles, manufacturing and energy management.

3.1 Automobiles and Transportation

The conveyance of people and goods from one point to another is a very important necessity to human existence. Wonderful exploits have been attained in the different modes of transportation over time. In modern day technology, CPS is paramount to the utilization of automobiles or vehicular systems. This spans from providing improved displays, entertainment and information including the management of motion and energy consumption. The study of Bhatia *et al.* (2010) analyzed the AUTomotive Open System ARchitecture (AUTOSAR). This provides cyber basis in the functions of modern automobiles. Specification, system analysis and implementation are involved in the development of automobile systems. AUTOSAR is specifically designed to handle system requirement specifications.

For enhancing road safety, Loos *et al.*, (2011) presented a formal verification of planned out automobile control system. The system proposes vehicle's optimization of its navigation planned to a certain location, while the coordination of different automobile actions is done so as to reduce or avoid collisions. The application of CPS to the usage of roads and highways to ensure safety of road users is one defining point in the technological advancement of road safety. Another application of CPS in the sphere of automobile transportation is the model for optimization of system performance deployed for unmanned CPS with wireless sensor network (WSN) movement (Yan *et al*., 2012). This primarily entails the vehicle receiving signals from the WSN for determination of movements and navigation.

Kantarci (2015) outlined a proposal for effective management of intelligent transport system. The study developed a route selection model for paramedics aided by the deployment of CPS which consists of user interaction components, route selection and alternate route optimization. In times of emergency when promptness and timeliness is important, this stems to aid the navigation of paramedics to abate unwarranted hitches like clumsy traffic situations. The integration of cyber systems with conventional transportation system birthed the term Transportation Cyber-Physical Systems (TCPS). This dwells on monitoring, coordination and control of different modes of transportation. The constructs of a typical TCPS are application, cyber space and physical space. Cyber space connotes the field where communications over networked computers occur, while the physical space refers to the physical occurrence in the real world. Attaining intelligent transport system deploying CPS involves the effective combination of advanced sensors with embedded computational systems technology synchronized with cellular, wireless and satellite technologies for efficient management of traffic flow, safety assurance and project situation awareness.

3.2 Health Care and Medicals

Improvement of digital technology has gone a long way in enhancing health care delivery. From the patients receiving treatment to the medical personnel saddled with responsibility of administering medication, the ripples of technological advancement has been tremendously felt. Milenkovic *et al*., (2006) stated that new innovations in wireless sensor networks (WSN), cloud computing and medical sensors are placing CPS as a viable candidate for health care applications consisting of in-home and in-hospital patient care. With this advancement in technology there are firm promises that in no time patients' conditions can be examined through CPS irrespective of the location disparity.

Sensors in the CPS set up apparatus are built to collect important patient information detailing health data. Wireless communication then serves as medium of collecting data to a gateway. However, data collected by the sensors can be stored in a server, and then made accessible by whoever needs it. Emphasis has been placed on data security since patients' data are confidential. This is strictly adhered to in ensuring ethical and legal compliance. The architecture of CPSs for healthcare systems can be either server based or cloud based. The server based is ideal for small architecture requiring individual maintenance. Whereas cloud based architecture ensures scalability, it is cost effective and easy to access for large systems. Like other fields, CPSs requires computational and communication process carried out simultaneously. Based on the application, identification of system composition is done by the system architecture. According to Lee *et al*., (2012), the devices used for medical cyber-physical systems are grouped into two based on their basic functionality, which is monitoring and delivery devices. Oxygen level monitors and bedside heart rate are typical examples of monitoring devices, while that of delivery devices are infusion pumps and ventilators.

Much has been said about patient's health record details and privacy. Data stored in cloud storage and the subsequent information gotten therein remains solely that of the patient. Restrictions are therefore placed against unwarranted acquisition of patient's health records or medical history. Legal and ethical principles are strictly conformed to when deploying CPS in medical practice.

3.3 Manufacturing

Manufacturing sector has been a huge beneficiary of technological advancement over time. From the era of using crude and non-sophisticated implements to the current times of global virtual workforce, nano-based preventive maintenance, internet of goods, cloud computing, there has been a glaring improvement in this sector. This sector's prominence to the economy of any nation has given it relative advantage over other sectors. Manufacturing has a pivotal role in the economic development of any country, with special emphasis on developing countries (Haraguchi *et al*., 2017).

As production systems are becoming more complex including with ever increasing demands for sophisticated goods by consumers, there is the need to rejig the processes and coordination of the assemblage of the different constituents making up the final end product. Shafiq *et al*., (2015) affirmed that mechanical systems alone cannot guarantee production of high volume, hence the application of information and electronic technology in the process of production. Heppelmann and Porter (2014) stated that there is the need for continuous monitoring of products, and analysis of operational data which could aid in the increase of efficiencies of established service systems and by formulating new hybrid business models founded on smart, connected products. CPSs are highly recommended in the processes of the manufacturing sector so as to attain the goals of Industry 4.0. Lee *at al*., (2013) asserted that integrating CPS with production, logistics and services in current practices of the industry would bring about transformation of current state of factories into Industry 4.0 factory with remarkable economic possibilities. Attaining the objectives of the 4th Industrial revolution can be attained by fusion of sophisticated network with intelligent production and process system. With this in mind, CPSs have a paramount role to play in attaining this objective.

The development of the CPS 5C architecture gives a general guide to the adoption of CPSs for manufacturing application. This is made of two main functional components. The first is the advanced connectivity that permits data acquisition in real time from the physical world and information feedback coming via the cyberspace. Secondly, the intelligent data management analytics and computational capabilities that makes up the cyber space.

3.4 Security and Surveillance

CPS has been firmly established in the area of security. Its application in this sphere has helped in curbing crimes and easy monitoring of private or public domains. One of such application is the use of alarm systems. This system establishes a connection utilizing the cyber connection through general packet radio codes with multiple accesses (Ma *et al*., 2010). With the deployment of mobile communication network, there is a synergy between communication control, terminal objects and users. The physical world is detected by the alarm using the terminal object which is then connected to the users. Reversibly, the user can as well control and monitor the physical world with the deployment of the communication system of the alarm.

This is one of such applications of CPS to security and surveillance. Defense units or security departments of countries deploy CPS for safeguarding territorial landmarks. Equally, it's used in monitoring existing facilities and structures of national prominence. Also, not forgetting private security outfits commissioned to undergo security duties for individuals, organizations (private and public). Such outfits deploy the use of CPS to undergo their task for effective and smooth running of functions.

CPS application is also felt in the security and surveillance of electric power grids. This dwells on issues like prevention of attacks of installed facilities, detection of theft or other unsavory experiences, mitigation of foreseen unwholesome events and restoration of faulty or ill connected sections (Ten *at al*., 2008; Mohajerni *et al*., 2010 and Kosut *et al*., 2011).

3.5 Power and Thermal Management

Power has grown to be one basic necessity for human existence, as almost all activities carried out is linked with utilization of power energy. Basically, a whole lot of other industries are highly dependent on this sector for effective functioning. However, the bane of modern power grid systems is reliability and efficiency (Moslehi and Kumar, 2010). With the prominence of the sector established, the optimization of the processes such as power generation, transmission, distribution, maintenance of infrastructural facilities cannot be over-emphasized. Over the years, emphatic efforts have been made to make this a realization. One of such moves is the application of CPSs in the processes of power generation, transmission, management and consumption of power and thermal energy. Yang *et al*., (2018) affirmed that the challenges faced by the controlling and optimization of thermal power plants under various boundary conditions and operational modes can be potentially handled by the application of CPS. The cyber and physical platforms making up the CPS can be operated deploying distinctive spatial and interacted within each layer with tight connectivity. Wan *et al*., (2013) designed an energy management framework (EMF) using CPS application having the capability of collecting the real time power consumption state and demand from autonomous electric vehicle (AEV) and smart grid charging stations.

3.6 Smart Homes/ Buildings

The study of Li *et al*., (2011) discussed a modeled CPS with cooperating architecture based on smart community architecture called Networked homes. CPS is vital to attaining in full the context of the term called 'smart home'. Activities like controlling the heating system or the security apparatus or deciding when to put down the curtains or possibly switching on electronic devices are executed in everyday living in a home. All these can be achieved with the *modus operandi* of CPS. In such set up, the actuators and sensors are programmed to enable its control via the internet which then aids the activities of the user through monitoring. Multifunctional sensors are incorporated into smart homes for measuring physical features. Mazumdar *et al*., (2016) deployed smart home living applications and smart videos surveillance in designing AXIOM (Agile, eXtensible, fast I/O Module) which developed hardware-software platform for CPS. The study of Kleissl and Agarwal (2010) aimed at designing buildings whose energy consumption annually is zero net. The study ascertained the likelihood of collaborative optimization of energy utilization by its users and IT equipment.

Singular units of smart homes collectively form what is termed a smart community. This is achieved with the networking of the smart homes to form a cluster thereby fostering communal living. Singular home units are tailored towards multi-functional sensors; also human controlled physical feedback is given when necessary to improve home security, community safety and home security.

3.7 Construction

The construction industry is infamously known for its retarded pace at embracing technological changes in its processes and procedures. This has inhibited the industry from maximally leveraging on the benefits such advancements bring along. Gross inefficiency is showcased in the construction industry delivery process, and it is in dire need of new innovations like adequate investment in cyber infrastructure (Anumba *et al*., 2010). This has been one of the perennial inadequacies of the construction industry over the decades. Kamara *et al*., (2010) posited that the construction industry is an ideal candidate for a step change due to its reoccurring problems like lack of certainty (in terms of quality, delivery date or cost), relatively poor productivity in comparison with other sectors, inadequate client satisfaction and inefficiencies as a result of out of date processes. The industry is in dire need for a change of operations and processes to meet the ever growing demands in many facets. Presently, CPS is not a prominent phenomenon in the construction industry. However, recent studies have showcased the possibilities on infusing CPS in construction processes.

Cheng and Teizer (2013) affirmed that physical construction and virtual models integration has shown great promise for activity monitoring and resource tracking which culminates into improvement of productivity and safety. For CPS application to construction, Akanmu and Anumba (2015) outlined two elements which are 'physical to cyber bridge' and 'cyber to physical bridge'. The 'physical to cyber' is the sensing process involving the deployment of sensors and other technologies for acquiring information on building components. Then, the 'cyber to physical bridge' connotes the actuation showing the effect of the sensed information on the system. Actuation in this context refers to control decisions from the information gathered by the sensors so that construction activities, equipment and building components can be controlled. The study of Akanmu *et al*., (2015) investigated CPSs approach in its application in the improvement of bi-directional coordination between physical construction processes and virtual models. The study adopted scenario development prototyping to demonstrate CPS integration in construction processes with specific emphasis on facilitating bi-directional coordination. Anumba *et al*., (2010) described the promotion of real time coherence affirmation between physical construction and virtual models. The study argues for efficient integration of design and construction processes with computational resources (such as virtual prototyping, wireless sensors, data fusion and real time tracking).

4.0 Key Benefits of CPSs Application

CPSs comes with a whole lot of benefits depending on the field it is being applied. Bhrugubanda (2015) stated that CPS creates the platform for solving of real time problems in modern age. It brings the provision of the interrelation of different technologies such as distributed systems, real time systems, control systems and wireless sensor networks.

Herterich *et al*., (2015) affirmed that CPSs offers the opportunities of downtime reduction of equipment and propelling efficiency of operations. In production processes, the integration of computation and physical processes leads to effective delivery which is a resultant of the synergy of both processes. Equally, innovations such as product cloud which is the location for storing and analyzing operational data of all connected products is a contributory factor for optimum delivery of the system. Such information gotten from analyzed data then helps in strategic planning, control of established models of production for better outcomes and as well as future system improvement. Its support for the evolving system re-sizing and reformation to achieve distinguished business opportunities cannot be overemphasized. Herterich *et al*.,(2015) asserted that the benefits accrued from implementing CPS in production processes are leveraging on operational performance data through engineering better equipment, operations equipment optimization, control and management of equipment remotely and trigger of service activities. The highpoints from CPS in production processes are attained when data from already installed industrial equipment is used for re-strategizing for the future. And also the continuous collection of data over time based on CPS can be used in predicting service activities for example carrying out routine maintenance as a result of wear and tear of machines.

The merits of innovative drive such as CPSs are of immense benefit to the medical practitioners, the recipients of medical care and the entire industry at large. Dogaru and Dumitrache (2015) noted that CPS aids adaptive treatments for general population's health from analyzed data. Patient's personal health records are documented for making informed decisions, to enhance precision of treatment, abating unnecessary inquiries that do not lead to positive outcomes of patients' conditions, minimizing the probability of re-hospitalization of patients by developing treatments to suit illness. Deploying CPS in healthcare delivery could helpful in getting expanded access to health education by the provision of valuable and useful information, also the networking helps specialist in service delivery (Hague *et al*., 2014).

Traffic system control performance has immensely improved over time with the adoption of CPSs in transportation traffic management. Bhrugubanda (2015) highlighted that intelligent transportation system can achieve optimized traffic control with the addition and installation of advanced digital devices and information systems in road traffic operation systems, thereby enhancing safety level and operational efficiency. CPS helps in harmonizing such data from input and output processes, thereby giving information on coordinated flow of networked systems which then aids in improving traffic management operations. Han and Duan (2017) outlined the applications of TCPS in vehicular transportation with the derived benefits. TCPS with respect to vehicle oriented CPS has helped in anti-skid control, avoidance of collision, autonomous driving and automated lane change. Vehicle-infrastructure CPS covers automated re-routing, traffic-based navigation, road condition querying, weather querying, while that of infrastructure oriented CPS includes traffic visualization, signal control, roadway construction and repairing preparation.

The construction industry is known to be slow in accommodating changes in processes from technological innovations and development (Renz and Solas, 2016). This has impeded the growth of the industry when compared to other industries with easy acceptability of new technological frontiers. Some scholars have placed it as an uphill task for revolutionary technological drive to be immensely felt in the construction industry. Teicholz (2013) opined that the construction industry with its current practices around the world might have an uphill task with technological innovations such as CPSs. However, with the introduction of Building Information Modeling (BIM) tangible improvements has been recorded with the dealings of the industry. The benefit derived from such application is the overall management of the project from its conception through construction, operation and maintenance. CPSs has had its fair share of developmental strides in the construction sector such as integration of physical construction and virtual models for improved modeling of intended facility, monitoring of resources on site and progress monitoring (Motamedi and Hammad, 2008). The adoption of CPSs would get rid of on field information gathering manually and also time (or events in real time) reduction of construction work processes. This helps in saving time in order to focus on tasks that are of more aggregate value.

5.0 Conclusion

A critical review of cyber-physical systems has been done in this study using existing literature on the subject. CPS has gained prominence in recent times and is highly sought after for its immense benefits during application to different fields of endeavor. Its overwhelming influence in these different areas has tremendously helped in efficient functioning as well as optimization in delivery. Some of the benefits of the application of CPSs include downtime reduction and propelling efficiency in operations in manufacturing processes. In medical healthcare systems, analyzed data acquired by CPS helps in adaptive treatment for general population health. There has been improvement in traffic management systems with the application of CPSs in transport systems. In security and surveillance, CPSs aids in the control and monitoring of physical world with the deployment of communication system

Industries like medicals and health care, security and surveillance and power and thermal management and manufacturing have all found their footing in the application of CPSs, but same cannot be said for the construction industry. Its foot-dragging disposition towards accepting technological innovation has been a major setback and has hindered the industry from benefitting from the enormous gains of the application of CPSs in its processes. Although recent studies have shown that there are great promises for the industry. In comparison to other industries, the construction industry is still lagging far behind in terms of the applicability of CPSs to its processes. Collaborative efforts among stakeholders will help spur the ease of acceptance. The teaching of modern technological innovations in construction processes should be encouraged in tertiary institutions. This would aid in the phasing process from classroom teachings to on-field practical experience. Workshops and symposiums should be regularly organized by professional bodies in the construction circle for educating professionals on recent technological innovations so as keep stakeholders abreast of developmental drives emanating from revolutionary world of digitalization. Modeling of intended facilities through virtual models and progress monitoring coupled with resource monitoring are some of the potential benefits of the application of CPSs in construction processes.

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AIGBAVBOA Clinton is currently the Vice-dean: Postgraduate Studies, Research and Innovation (PSRI) of the Faculty of Engineering and the Built Environment (FEBE) of the University of Johannesburg. He also serves as the Head: Sustainable Human Development and Construction Research Centre, in the Department of Construction Management and Quantity Surveying, School of Civil Engineering and the Built Environment, FEBE. He is a Professor in the Department of Construction Management and Quantity Surveying, University of Johannesburg, South Africa. As a Ph.D. candidate in 2013, he was among the top 10 researchers in UJ; while in 2014 and 2015, he was the leading research output contributor in the University. Prof Aigbavboa has published more than 400 peer-reviewed articles in journals, conference proceedings and in book chapters.

OKE Ayodeji Emmanuel is a Quantity Surveyor by training and a Ph.D. holder in the same discipline. He bagged his B.Tech degree in Quantity Surveying from Federal University of Technology, Akure, Nigeria in 2006 with a first class (Hons.). He is a reviewer for various local and international reputable Journals. To his name and in collaboration with academia within and outside Nigeria, he has authored a good number of journal and conference papers both locally and internationally. He received 2016 Emerald Literati Award for the article on Structural Equation Modelling of Construction Bond Administration, as a highly recommended paper in the Journal of Financial Management of Property and Construction. He is one of the authors of the book titled sustainable value management for construction projects. He is a Research Fellow at the Department of Construction Management and Quantity Surveying, University of Johannesburg.