Utilizing Industry 4.0 on the Construction Site: Challenges and Opportunities

Christopher J. Turner, John Oyekan, Lampros Stergioulas, and David Griffin

***Abstract*—In recent years, a step change has been seen in the rate of adoption of Industry 4.0 technologies by manufacturers and industrial organizations alike. This article discusses the current state of the art in the adoption of Industry 4.0 technologies within the construction industry. Increasing complexity in onsite construction projects coupled with the need for higher productivity is leading to increased interest in the potential use of Industry 4.0 technologies. This article discusses the relevance of the following key Industry 4.0 technologies to construction: data analytics and artificial intelligence, robotics and automation, building information management, sensors and wearables, digital twin, and industrial connectivity. Industrial connectivity is a key aspect as it ensures that all Industry 4.0 technologies are interconnected allowing the full benefits to be realized. This article also presents a research agenda for the adoption of Industry 4.0 technologies within the construction sector, a three-phase use of intelligent assets from the point of manufacture up to after build, and a four-staged R&D process for the implementation of smart wearables in a digital enhanced construction site.**

***Index Terms*—Cyber–physical systems, digital twin, industrial internet, Industry 4.0, Internet of Things (IoT), wearables.**

I. INTRODUCTION

THE CONSTRUCTION site has seen many advances and has benefited from the uptake of new technology. However, such advances have been in the areas of building methods, materials, plant, and machinery. Even with such progressive changes, productivity rates in the construction sector are still among the lowest in industry [1]. This is partly due to the reduced skill requirements needed for the entry to the construction industry. The low entry requirement leads to a larger workforce but a low per person increase in productivity. In addition, a shortage of construction professionals, such as engineers, project managers, and supervisors, is predominant in the construction industry. This is associated with an assumed image of the construction sector as being unattractive to such skilled workers.

In the long term, increasing complexity in onsite construction projects, such as the Burj Khalifa, London Shard, HS2 high speed rail, and an ever-reducing highly skilled workforce, will eventually lead to problems in sustaining the sector.

This will increase the probability of safety-related issues and further reduce the sector's productivity statistics [2], [3]. These problems call for novel ways to train, support, and increase the productivity values of individual workers.

Improving productivity is a critical issue because it is the most important index in measuring the standard of living within nations and their prospects for further economic growth [1]. In fact, poor productivity and skill shortages have led to high construction costs, delays in construction projects, and poor sustainability practices in the construction sector. The construction industry makes extensive use of natural resources, such as water, cement, sand and gravel, clay, concrete, and marble in building materials. Furthermore, it consumes fossil fuels, such as diesel and petrol, for building machinery and transportation. All of these contribute to global emissions and the depletion of natural resources at an unsustainable rate. Improving the productivity of workers will ensure that natural resources are used more efficiently overall.

In fact, in the U.K., the government has set out an initiative called "construction 2025" in which construction projects must be finished 50% faster with 50% less greenhouse gas emissions in the built environment and 33% reduction in the initial cost of construction and whole life cost of assets [4].

One of the ways the construction sector is planning to achieve these targets is through the application of Industry 4.0 tools (see Fig. 1). The construction industry is seen as one of the sectors lagging behind in the use of modern industrial digital tools. The "Made Smarter UK" review has identified construction as one of the sectors that could benefit from the Industry 4.0 revolution [1]. Through the use of Industry 4.0 tools, workers could be supported with knowledge and information on assessing the impact of their various activities on the environment and how efficient or sustainable they are.

Toward this, in recent years, the worldwide construction sector has begun to adopt digital technologies in the pursuit of operational and productivity gains. Termed Construction 4.0, the adoption of Industry 4.0 technologies [5] is seen as an enabling force that will usher in an evolution of the construction sector and revolutionize its practices and techniques.

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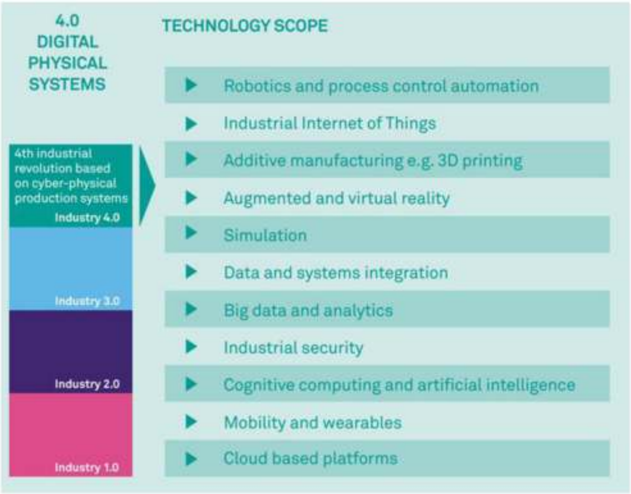

Fig. 1. Technology scope of industry 4.0, reproduced from [1].

The range of activities happening on construction sites present a lot of interesting research challenges. In this article, we focus on how a "connected" construction site (from offsite activities to onsite activities to after construction activities) can be achieved with Industry 4.0 technologies toward improving efficiency, improving sustainable practices, and improving worker safety.

This article is organized with sections related to the following key Industry 4.0 technology areas: data analytics and artificial intelligence (see Section II), robotics and automation (see Section III), building information management (BIM; see Section IV), smart wearable technologies (see Section V), digital twins (see Section VI), and industrial connectivity (see Section VII). This article then analyses the main challenges and opportunities for the construction sector in Section VIII, with an overall summary provided in Section IX.

II. Data Analytics and Artificial Intelligence

The use of data analytics and artificial intelligence has gained attention within certain parts of the construction sector. Real-time data analytics, both onsite and offsite, can help improve risk detection and assessment. It can provide new capabilities in terms of predicting incidents and issuing early warnings and alarms to workers via smart wearables. It can also support automated learning systems that can manage risks on site and in real time. Capturing data on the progress of construction projects, worker activities, vehicle activities, weather conditions, and conditions on site in data warehouses will provide the fuel needed to drive data analytics and artificial intelligence algorithms. Scheduling and optimization algorithms could then be deployed to derive new strategies to address possible issues arising during an onsite construction project.

Collecting, managing, processing, and analyzing time-stamped data from many construction sites will enable the building of an historic database, which could be mined according to needs. This could help generate wider insights into the construction sector. It also enables the derivation of new efficient construction rules and techniques. Also, the insights can then be used in decision making and strategy building for onsite construction management on a massive scale.

Toward the aforementioned, artificial neural networks have been used in the construction industry to mine past knowledge for the estimation and prediction of the compressive strength of concrete. This has proven insightful in understanding how the five key constituents of concrete, namely water, cement, metakaolin, fine aggregate, and coarse aggregate, affect the quality of concrete and, consequently, the quality of the building [6]. In the absence of highly skilled workers, an artificial intelligence (AI) system could be utilized in training and supporting less experienced builders.

In order to monitor the current progress of construction projects and the structural health of complex structures during construction, modal parameters, such as natural frequencies, damping ratios, and model shapes, are essential. These data have been used with highly efficient Bayesian methods for dynamic structural characterization and identification [7]. These data are collected by intrusively placing sensors on the structure being built. Nevertheless, nonintrusive methods, such as the use of red, green and blue (RGB) cameras, can be another approach for capturing the progress of construction projects. Exploiting data streams from RGB cameras is being pioneered through the use of image processing techniques to extract useful information from captured digital images and video [8], [9]. Data currently collected include areas in which worker activity is currently concentrated, location of raw materials, and flow of raw materials and earthworks. Such artificial-intelligence-equipped RGB data streams could ensure that earthworks are completed efficiently and effectively. This is useful in reducing greenhouse emissions going into the environment [10].

Most construction projects go over budget due to scheduling issues, poor planning, and lack of adequate information at the initiation phases of a project. This invariably reduces the output of each worker and hence productivity of the entire project. The connected database concept and analytics will enable more accurate cost estimation through the use of knowledge gleaned from previous projects. For example, Asadi *et al.* [11] investigated the development of prediction models that identified the causes of delays in a construction project. Bayram *et al.* [12] developed radial basis function and artificial neural network models for preliminary construction cost estimation. In this ecosystem of data-driven tools, cost estimation software can also be integrated with automated planners for earthworks during onsite construction projects. This would ensure optimal utilization and route planning of vehicles in onsite construction leading to substantial savings in both cost and time [11]. Such use of AI could be extended to control swarms of autonomous vehicles and robots in order to drive onsite construction productivity higher. All the aforementioned can only be achieved if data streams from sensors are connected to data warehouses and data analytics platforms for insight generation and subsequent use by workers and robotics or automation equipment.

III. Robotics and Automation

Novel uses of robotics within the construction industry include the use of unmanned aerial vehicle and quadruped robots.

They are commonly used to survey construction sites and for collecting data to generate 3-D models of buildings [13]. They could also be used to aid workers by carrying heavy tool kits. Nevertheless, Aripin *et al.* [13] highlighted a number of potential barriers to the adoption of robotics and automation within the construction industry. For example, the complexity of tasks to be performed by robots in construction is much higher than encountered in other industry sectors. This is potentially due to the high variability and dynamism that is encountered in onsite construction sites.

One way of solving this problem is the application of current manufacturing techniques via offsite modular building manufacture for onsite assembly. This approach ensures that well-established manufacturing automation technology can be applied to construction. In such an approach, digital innovations from Industry 4.0 can be applied in the areas of manufacture and supply chain [14]. They could provide an opportunity for the just-in-time manufacture of a building's constituent components and modules. In a connected construction site concept, data from onsite activities could be sent to the offsite manufacturing plant so that changes required in how a module is manufactured are immediately communicated just in time. Example data could include parameters concerning dampness or humidity and their effect on housing modules stored onsite. The findings from the analysis of such data may lead to the application of additional layers of paint to the wood exterior of the modules to add protection from the elements.

Furthermore, "digital fabrication" methods have led to the notion of "adaptive manufacturing." Adaptive manufacturing introduces the concept of highly flexible machines, which are capable of customized part production and utilized to enable new cost-effective building methods [15]. Such methods have the potential to increase the efficiency and productivity of the construction sector as a whole. For example, in one case study, examining the use of a robot to construct concrete wall structures, Garcia de Soto *et al.* [16] reflected on the changes in the workforce that digitization could bring. The possibility of combining design, planning, and construction tasks lead to the potential for the elimination, modification, and combination of once separate jobs.

Additionally, new digital 3-D printing technology now makes it possible to use additive methods to build structures via block laying robots, 3-D structure welding robot arms, or a concrete depositing robot arm. These technologies offer much promise to the construction sector and create opportunities to improve productivity. The process delivered by additive building is a recent construction research trend that relies on state-of-the-art digital technologies such as computer-aided design (CAD). The process is capable of printing building structures in-situ with added advantages, such as reduced exposure of workers to risks encountered in conventional construction projects and overall reduced cost of construction [17].

In the near future, the use of swarms of autonomous vehicles controlled from a central hive could be deployed on construction sites to assemble buildings. Such a hive will possibly make use of digital twin technologies in order to accurately schedule and plan the individual vehicle actions. Furthermore, the use of AI will be relevant in adapting to changes in environmental conditions toward meeting deadlines, whereas robust communication protocols will ensure that the hive is connected to the vehicles. Such technology will ensure that parts of the construction process will be more reliable thereby improving productivity and efficiency on site [18].

Apart from guiding robots in additive building of structures, digital tools, such as BIM, are also being used to aid workers during installation of cables, fixtures, pipes, and other internal housing components.

IV. BUILDING INFORMATION MANAGEMENT

The practical use of the BIM concept has recently taken on greater importance within construction industry organizations. When compared with the paper equivalent, BIM models enable building plans to be easily accessible via digital devices and provide a route to the real-time monitoring of building progress. Whyte and Hartmann [19] noted the potential of BIM in breaking down barriers between previously siloed activities in order to provide better integrated and flexible design and build stage processes. Furthermore, Zhang *et al.* [20] investigated the use of BIM and 4-D models for automated identification and prevention of construction worker fall hazards onsite. In their work, an automated rule checking algorithm was used to detect safe working areas and edges in a building. These data were then further analyzed to prevent worker falls. The benefits of such a system can be an important driver for the formal adoption of BIM as part of the standard safety planning processes for construction projects and as a real-time automated hazard checker. Safety is also a theme explored by Malekitabar *et al.* [21] who identify the main risk drivers and define a set of rules derived from the analysis of accident reports. The approach of Malekitabar *et al.* [21] provides a methodology that may be used by expert systems to underpin digital automated approaches to conformity and risk identification. Furthermore, Park and Kim [22] set out a framework and componentize the three elements of safety management, namely education and training, planning, and inspection.

These elements can be supported through the use of BIM to cheaply and safely educate low skill workers before they actually perform tasks. It could also aid them in planning out activities and inspecting their progress and mistakes. Such setup becomes even more powerful when combined with the immersive capability of virtual reality (VR). This view is further supported by Li *et al.* [25] who also noted that the uptake of augmented reality (AR) could ensure the onsite safety of construction workers in real time. This ushers in various interesting applications, such as "on the job" safety monitoring and hazard identification.

Nevertheless, although examples exist of BIM and VR being used as tools to communicate construction models to interested parties, there are currently limited examples of "connectedness" between such models and real-time data streams [23]. As a result, Wang *et al.* [23] discussed how 4-D CAD model (animated CAD models often utilize a timeline) and AR can be used to enable in-situ interaction with building plans and access BIM data [23] (see also [24]). Furthermore, Park and Kim [22] made the case for real-time communication between workers and construction site supervisors through the use of AR for both safety and tracking purposes.

In the aforementioned, the Internet of Things (IoT) is one of the key technologies that can enable the linking of BIM with real-time (or near to real time) data. Combining BIM with IoT opens up the value of treating buildings and their components as intelligent products that are capable of providing information concerning their correct assembly and real-time status both during and after construction. From a system perspective, the combination of IoT and BIM (with BIM providing information on how the components are connected to each other) enables buildings to participate in construction management processes and the related supply chains. In the work of Boton [28], such systems can also be utilized as real-time forums for the discussion of construction issues during the design and building of new buildings.

Nevertheless, despite the availability and potential to deploy various sensing modalities in onsite construction, crucial productivity data on the important element, the human, are still missing. This missing data link is crucial because most of the work completed on construction sites is still heavily manual in nature. As a result, Dave *et al.* [26], [27] proposed that efforts should be focused to bring about a full lifecycle appreciation of construction projects supported by appropriate digital solutions, sensors, and smart wearable technologies.

V. SMART WEARABLE TECHNOLOGIES

Smart wearable technologies make use of a multitude of sensing technologies to detect the movement and psychological state of individuals, including the environmental conditions in which they work. Cheng *et al.* [29] investigated the use of wearables to collect data on the spatio-temporal activity and thoracic posture of workers. The wearable system was made up of a commercial physiological status monitoring (PSM) system equipped with a wearable three-axial thoracic accelerometer. The data collected were processed at a remote hub to perform real-time productivity assessment. Jo *et al.* [30] presented a robust construction safety system that interfaces with a global positioning system communication unit. Such a system enables real-time information of construction site resources, such as workers, to be obtained and managed effectively. One of the ways the system is being used is in preventing collisions between workers and heavy equipment.

In a step toward making sensors even less intrusive, in [31], the use of smart fabrics by construction workers to provide an ecosystem in which safety and information provision is at the heart of the wearable technology was discussed. Such a smart wearable fabric could also be used to provide both tactile and audio information to the worker via integrated vibrators and microphones [31]. While such fabrics are still in development, there are more readily accessible wearable devices, such as smart watches, that could replicate at least some of the promised functionality.

Such smart watch-type wearables enable workers to receive information from a remote AI module and delivered to them in a location and context-relevant format. However, this requires an effective method of transferring data to a remote location and the retrieval of knowledge from devices. Due to size limitations, the wearables have communication constraints that need to be addressed. This is further discussed in Section VII on industrial connectivity. Furthermore, data privacy and cyber security are challenging issues that still need to be addressed before workers have enough trust to use them.

Nevertheless, by leveraging the data captured by smart watches, it is possible to envisage a four-stage R&D process toward the improvement of construction workers' health, efficiency, injury reduction, and associated costs.

1) The first stage should involve an ethical review and anonymization of data and seek the voluntary consent of workers. This makes it possible to acquire baseline data covering worker physiological factors and wider health-related, psychological, and attitudinal information. This step, conducted onsite and offline/in the lab, enables gathering of benchmark parameters related to the target population.
2) The second stage involves a feasibility study with a pilot group of volunteers conducted in two different settings: on the work site and in the lab. Practically, this step combines design improvement elements with physio-psychological assessments. On the one hand, it makes it possible to compare and contrast different conditions on work sites, such as cases of extreme weather, lighting conditions, pollution, visibility, and site strategies (e.g., night work, extended shifts, and modularization). On the other hand, it offers an opportunity to study workers in relation to intraindividual factors, intrinsic fatigue, attentional capabilities, and work-related and general performance tasks under the aforementioned conditions. This phase will enable a theoretical and computational model to be put forward and support plans for environmental and behavioral interventions.
3) Further to the previous stages, a longitudinal implementation in the workplace represents the third step; this entails trialling the model resulting from phase 2 on the worksite. Workers can be monitored for 12- to 24-h periods over weekly batches with included selected interventions (e.g., changing rota or providing feedback to workers on physiological patterns). The data obtained can then be coupled with data on particle exposure, weather conditions, noise, and worksite features to obtain information on sleeping quality and job satisfaction. This phase can also comprise the development of a dedicated digital platform, which may include geospatial information toward a holistic "connected system" for improving construction workers' safety.
4) Finally, based on the results from previous stages, it is possible to realize a gradual scale-up at a national and international level. The results would ultimately deliver policy solutions to the important wellbeing issues that construction workers face.

Toward the development of a holistic "connected system" for construction activities, the Industry 4.0 concept of digital twins could provide an effective framework.

VI. DIGITAL TWIN

The concept of “digital twin” to capture real-time activity and support predictive intelligence for decision making is gaining in popularity. The digital twins approach offers the possibility of reproducing a construction site virtually across geographical regions using network technologies. It offers users the ability to create and test hypotheses before actual implementation [32]. This capability provides unprecedented data and knowledge on working sites. It offers the ability to spot trends and anomalies that will feed into the next generation of policies for hazardous working environments and management practice. However, as with most of the technologies discussed in this work, the digital twin concept still faces challenges in its adoption by the construction industry. One of the issues is how digital twins should be used in such a dynamic and real-time environment. Another issue is the format of data presentation or visualization to the users.

The mode of data visualization within a digital twin is an important consideration, especially when communicating multimodal complex information coming from various sensors and sources to users. Due to the limited cognitive bandwidth of humans, this is a challenge but could also be an opportunity. The ability to relay information in a context and location-sensitive fashion may be the key to digital twin adoption in construction. Technologies such as AR provide a unique visualization solution that enables a worker to document, monitor construction site activities, and markup important information for a digital twin to intelligently run offline hypotheses generation and analysis. Furthermore, digital mark-ups and important messages could be placed and left in the construction environment for use by other workers in a fashion similar to stigmergy in natural ants.

For example, the approach outlined by Zollmann *et al.* [18] allows construction industry professionals to view building details overlaid in real time on partially built structures via AR. Their system also provides annotated live views with comments for others to read when they view a particular area on site.

Discrete event simulations (DES) can be used to run various hypotheses in a digital twin in order to provide a more accurate estimate of the effects of workers’ actions on construction activities. Such simulations may be viewed as superimposed AR visualizations overlaid onto real-world scenes and viewed on-site by construction workers. Such work has been undertaken in the modeling of factory production lines [32], [33]. The digital nature of BIM further supports this possibility and provides a framework for building navigation on large-scale and complex construction sites [34]. This is because BIM models already semantically describe many components related to the fabric and dimensions of buildings, and so a 3-D simulation or AR view of a facility can be generated with relative efficiency. Such use of ontology features to describe physical geographic data in BIM could also provide a basis for communicating the work carried out by automated and autonomous machines in the future [35]. For example, a template process as suggested by Boschert *et al.* [36] could be used to populate a digital twin to record what decisions were made by the machine. Also, environmental conditions that led to that decision could be recorded. This makes it possible to have a system that has a friendlier human–machine interaction interface with a human-readable traceable decision process.

Such use of BIM in a digital twin in this way will enable traceability for later analysis and improved designs at a system level [37]. Also, the application of BIM in digital twins provides better visualization, tracking of worker locations (through utilizing radio-frequency identification (RFID) tagging), and an improved level of contextual information. Through the use of worker positions, geometrical layout of buildings, contextual information, and DES, it will be possible to relay real-time warnings to machines, workers, and supervisors when potentially dangerous situations are identified.

In such a modern “connected” construction site, multiple data sources can be combined and analyzed to provide operational and strategic-level insights for improved site management, enhanced cross-site safety, and more efficient decision making (e.g., team and plant deployment, earthwork planning, and overall workforce management) [38]–[40]. All the aforementioned will invariably improve the productivity statistics of the construction sector. As more external data sources (such as remote weather stations) become available to smart infrastructure projects, interoperability of systems will be required. Such connectivity will become increasingly important in order to ensure that the benefits of Industry 4.0 are fully realized in the construction sector.

VII. INDUSTRIAL CONNECTIVITY

The connection of remote devices, data sources, digital twins, artificial intelligence modules, and smart wearables to each other or to a base can only be achieved through the use of a variety of communication protocols. In the age of the IoT, there are a number of communication protocols that can be selected. However, these protocols have both their advantages and weaknesses depending on their application in construction. The ability to be able to obtain real-time information from a construction site enables construction site managers know where assets are and gives them the ability to make quick informed decisions. This provides improved scope for projects to be completed on time [41]. Existing literature that explore methods for the augmentation of construction objects with autonomy, awareness, and the ability to interact with their vicinity are now prevalent [42].

By integrating AI with IoT, such smart construction objects could offer safer, greener, and more efficient structures than in previous decades. In order to achieve this, the potential use of IoT objects is being investigated widely. IoT devices are typically made up of sensors, a board with limited computational resources, and a communication protocol [43]. Communication protocols could range from a few meters—as in the case of Bluetooth—to several thousand meters in the case of cellular technology (see Table I).

Apart from their use in collecting real-time information from a site and coordinating sensed events, IoT-equipped devices have been investigated in the context of monitoring how close field workers and outsiders are to hazard zones at all times, with the

TABLE I
SHOWING DIFFERENT COMMUNICATION PROTOCOLS AND THEIR FEATURES

Communication Type	**Standard**	**Frequency**	**Range**	**Data Rates**
Bluetooth	Bluetooth 4.2	2.4GHz	50-150nm	1Mbps
ZigBee 3.0	Based on IEEE802.15.4	2.4GHz	10-150m	250Kbps
WiFi	Based on IEEE802.11	2.4Ghz and 5GHz bands	Approx 50m	150-200Mbps, 600 Mbps maximum
LoRaWAN	LoRaWAN	Various	2-5km (urban area), 15km (suburban area)	0.3-50 kbps
Cellular	GSM/GPRS/EDGE (2G), UMTS/HSPA (3G), LTE (4G)	900/1800/1900/2100MHz	85km(GSM); 200km (HSPA)	35-170kps (GPRS), 120-384kbps (EDGE), 384Kbps-2Mbps (UMTS), 600kbps-10Mbps (HSPA) 3-10Mbps (LTE)

aim of preventing accidents in both large-scale and small-scale construction sites [30], [22]. In [30], ultra-wideband sensing technologies were used to enable the control of electronic control actuators on heavy equipment and stop their maneuvering if a worker is in danger. This was made possible because of the ability to achieve a local network of interconnected devices on a construction site. However, the possibility for potential construction site security breaches is opened once site infrastructure is digitally connected via the internet. This risk was explored by Maggi *et al.* [44] who identified security flaws in radio frequency (RF)-controlled construction machinery. These authors proposed that manufacturers of such RF-controlled plant should utilize practices developed for consumer technology and design in measures, such as rolling codes, to provide an additional layer of security. In work by Oesterreich and Teuteberg [24], the cyber risk of handheld electronic devices and their interactions with enterprise information systems is raised along with concerns about levels of data access in such collaborative organizational structures.

Dave *et al.* [26], [27] went on to observe that a major obstacle to data communication with IoT is the lack of generic interfaces between enterprise software vendor components and highlighted the potential role of open messaging interface/open data format (O-MI/O-DF) IoT standards. The MTConnect standard allows for compatible production assets to be remotely monitored without regard for machine type or manufacturer. In Bisio *et al.* [45], Bluetooth low energy tagging was utilized with a smartphone's ability to sense multiple connected devices in a local environment. This was then used to track construction site assets through the use of a custom-designed tracking app. The authors went on to use the detection and tracking of building site assets to explore the creation and provision of context awareness to connected devices. This particular approach is notable due to its ability to track assets in environments that are normally quite challenging for normal IoT sensor networks to operate [45].

In [46], a framework is proposed for the collection of a set of generic machine parameters from a range of machines provided by one machine tool manufacturer. Future research by Edrington *et al.* [46] involves the development of a data repository suitable for other brands of machines and machine tools. Such data repository would provide mechanisms to ensure complete analysis, advanced monitoring, and reporting of data.

The Open Platform Communications/Universal Architecture (OPC/UA) standard and message queuing telemetry transport protocol are increasingly used by multiple machine manufacturers and constitute a much-utilized format for the transfer of data to and from IoT hubs. The OPC UA standard, while comprehensive in its specification, can be complex and expensive for an organization to implement. In addition, the IoT messaging standards O-MI and O-DF provide standards pertaining to lifecycle management and are now seen as more general interoperability enablers for Industrial IoT applications.

Apart from the type of communication protocol used, the format of transferring sensed data and messages to other devices or a hub is equally important. Liyanage *et al.* [49] discussed the use of semantic web technology, ontology, and use of eXtensible Markup Language (XML) metadata descriptions for information exchange in e-maintenance [49]. Grangel-Gonzalez *et al.* [50] took the semantic communication notion a step further by producing a metadata software shell for Industry 4.0 components. The approach is based on resource description framework and Web Ontology Language and allows for new functionality, described by ontological elements, to be integrated into the communication framework with minimum disruption [50]. By combining with machine intelligence, such a framework could act as an enabling protocol for automation efforts in onsite and factory offsite operations alike. For example, Shahriar *et al.* [51] discussed the utilization of the MTComm standard with semantic ontology for the communication of manufacturing operations via Internet technology. Their study also involved the use of a cloud-based implementation for the real-time interactive control of machines in a test bed.

In a review of data format standards related to asset management, Koronios *et al.* [47] noted the increasing use of XML as a data description standard along with OPC for industrial system intercommunication. The work of Henßen and Schleipen [48] examines the role that the AutomationML mark-up language can play in simplifying the use of OPC UA models with existing datasets and streams expressed in XML. According to Henßen and Schleipen [48], the use of OPC UA directly is a complex task. Nevertheless, utilizing AutomationML mapping to OPC UA opens up the opportunity of streamlined connectivity with OPC UA compliant systems and manufacturing systems. So, even though OPC UA is likely to gain more ground in use for communication between onsite machines, there is still work to be done to ensure its seamless use among different machine manufacturers.

VIII. Discussion

As discussed in [52], there is still scope for the formation of new perspectives on the use of Industry 4.0 in the construction industry. Current reviews on the use of Industry 4.0 in the construction sector have examined specific Industry 4.0 technologies or their combined utilization for various purposes. For example, Dallasega *et al.* [53] and Alaloul *et al.* [54] focused on the use of Industry 4.0 technologies in construction supply chains from a management perspective, whereas Maskuriy *et al.* [52] focused mostly on the use of BIM for improving quality and productivity of construction. Maskuriy *et al.* [52] also discussed the issues of automating the design and construction processes while handling heterogeneous data. This article is the first study to present

1) a three-phase use of intelligent assets from the point of manufacture up to after build;
2) a four-staged R&D process for the implementation and application of smart wearables in a digitally enhanced construction site;
3) the first attempt to take a holistic connected view of using Industry 4.0 enablers on a construction site to improve productivity.

Productivity in the construction sector is the most important index in measuring the standard of living of nations, economic growth prospects of nations, and their social prosperity. Productivity is currently very low in the construction sector. To improve productivity, this article discusses how interconnected Industry 4.0 enablers could be used. It also explores the challenges and barriers these enablers would need to overcome to ensure a holistic interconnectedness between them.

It is clear from this research that how data are generated, transmitted, stored, used, and transmitted will be critical in the next generation of construction methods. Furthermore, bringing together and connecting all the necessary components of Industry 4.0 to realize a “connected” construction site will be necessary to derive the benefits of Industry 4.0 in the construction sector. The type of data generated by IoT devices might need to be taken into consideration when designing and building new data analytics pipelines for knowledge extraction and presentation. Furthermore, communication bandwidth will be an issue as the number of IoT devices on site increases. One way of addressing this is through the use of data reduction techniques, such as principal component analysis and edge node computations, to send high-level status data to a digital twin for decomposition and usage. The choice of communications protocol to use currently depends on the application. In the future, a combination of communication technologies with a common data exchange protocol backbone might be needed in order to ensure that plant manufacturer equipment can seamlessly interact with each other. A challenge of such an infrastructure would be to enable the interoperation of different communication technologies while dealing with their inherent strengths and weaknesses. Such seamless operation will support the deployment of digital twins utilizing two-way data links to robotic (cyber–physical) plants, IoT devices, smart fabrics, and intelligent products or assets. The use of “intelligent” assets [55] could provide sufficient data to enable, through the use of appropriate data mining and analytics approaches, intelligent redesign of onsite construction layouts.

In Table II, we propose a three-phase approach for the potential utilization of modular building components as sensorized and wirelessly connected intelligent assets. Such assets could take part in their own manufacture and share data with the manufacturing process to assist with the insertion of its subassemblies and its maneuvering for various machining actions [56]. On site, such an intelligent modular wall section could assist with its fine positioning and attachment in relation to other already assembled building sections (with the potential for such positioning detail to be relayed to workers wearing AR headsets). In the completed building, modular wall sections may be able to relay information back to a householder concerning the temperature and humidity of room or area. The construction company and manufacturer may also wish to receive periodic performance data from certain building components. In terms of the “intelligence” component of the asset, this may be composed of a sensor pack consisting of onboard edge computation and wireless connectivity with an onboard power supply. Furthermore, at the construction site, swarms of autonomous robots could work with each other to clear the site and move dirt in a coordinated fashion.

In Fig. 2 and Table II, a three-phase approach is demonstrated in the context of the digital construction site. Fig. 2 also provides an overview of the through-life relevance of Industry 4.0 technologies not just at manufacture and assembly stages but also in the monitoring and operation of completed buildings.

Table III presents a summary of additional research areas focusing on the investigation of the technologies outlined in this article for the application to construction sites. This includes the application of digital twins to enhance safety practices across construction sites. This opens up the possibility of providing a new agenda for the construction industry and informatics researchers alike. R&D into the application of captured data within a “digital twin” would enable assets to be modeled accurately and provide predictive trend information regarding serious safety incursions. Furthermore, such a capability would dramatically improve local decision making should changes or modification of a construction site layout be required.

It is clear from this research that the construction industry would benefit from the use of Industry 4.0 digital technologies, although it is still the case that to this date their uptake and application within the sector has been limited. The increasing complexity of modern construction projects is now acting as a driver for interest in the possibility of creating digital representations of the construction site. Planning and scheduling

TABLE II
INTELLIGENT ASSETS IN CONSTRUCTION: THREE-PHASE USE

Intelligent Asset	**Manufacture**	**On-site Assembly**	**In use**
Scenario/Application	An intelligent modular wall section being manufactured is able to share data with the manufacturing process to ensure in time delivery of sub-components and assist with their insertion.	A modular wall section being incorporated into a building is able to assist a builder by providing information regarding its fine positioning and attachment in relation to other already assembled building sections.	• A modular wall section is able to relay data back to a house owner's intelligent hub. • Data relayed include house temperature and humidity of wall section (perhaps to alert about water/damp ingress). • Provided consent is given, it might also be able to send data back to manufacturers.
Potential Sensors to apply at each phase.	Typical embedded sensors could include orientation, vibration and temperature sensors.	Typical embedded sensors could include orientation, RFID and IR sensors to ensure correct positioning and alignment between panels.	Typical embedded sensors could include temperature, humidity, lighting, chemical sensors to measure pollutants and carbon monoxide levels.
Communication types and properties required at each phase.	Short range communication protocols such as Bluetooth or ZigBee will ensure that communication stays local but also allow a mesh type network to be constructed for easy transferring and sharing of data.	Depending on the size of the construction site medium to large range communication protocols such as Zigbee, WiFi or LoRaWAN could be useful in ensuring site wide communications between assets and workers.	• Typical communication protocols could be short range such as WiFi, Zigbee or Bluetooth. • If consent is given, internet technology could be used to transmit the data out of a user's home to the manufacturer's factories.
Potential data use in digital twins at each phase	• Process conditions such as temperature and vibration could aid in identifying optimal process parameters and predicting breakdowns; • Data from sensors will be used for inventory update and simulation	• Positioning data sent in real time to workers to communicate exact proximity to work pieces. • Alerting workers to potential dangerous unseen situations • Live feed of time and motion data to construction schedule	• Data could be used to inform the next generation of products for the next buildings allowing for automatic updates to designs. • Data could be played back to assess how the structure changes with environmental conditions and usage.

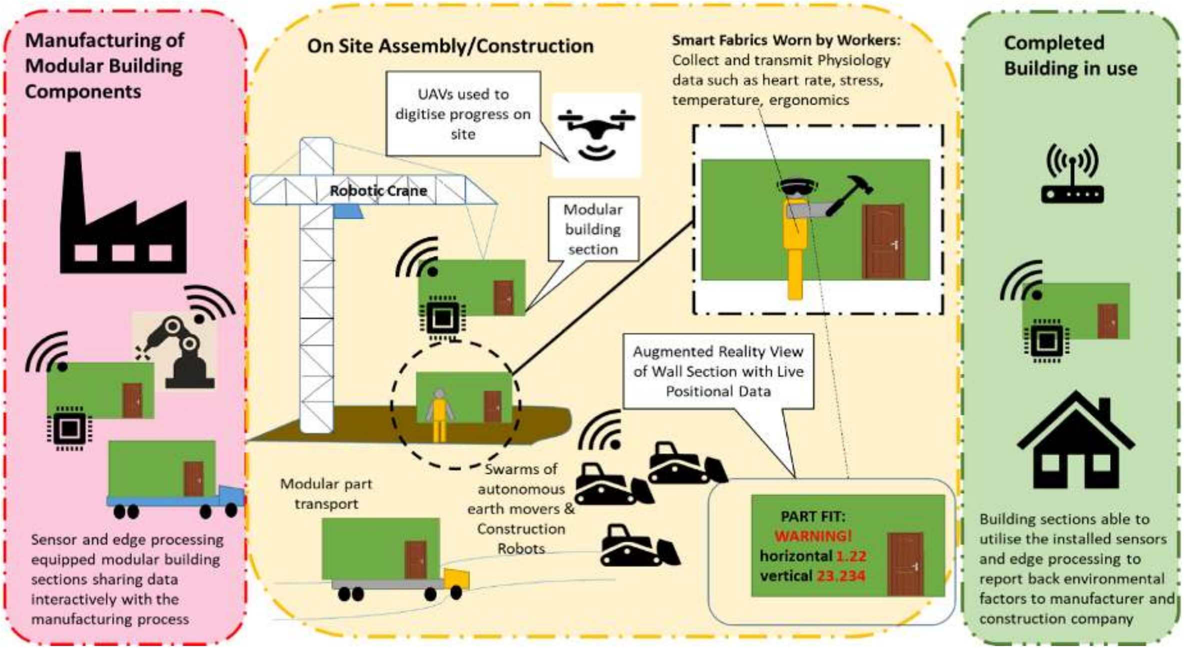

Fig. 2. Industry 4.0 equipped construction site. As shown in the figure, the reduction of personnel onsite due to the use of robotics and automation will lead to a reduction in lives lost due to fatal accidents. Greater process efficiency will contribute to a reduction in onsite greenhouse gases by up to 365 000 ton globally, and efficiency cost savings will be passed onto consumers. Furthermore, living standards will improve due to the application of digital technologies enabling higher quality construction [1].

TABLE III
RESEARCH AGENDA FOR THE ADOPTION OF SELECTED INDUSTRY 4.0 TECHNOLOGIES IN CONSTRUCTION

	Programme	**Vision**	**Impact and Research Agenda**
1	The next Generation in the use of site sensor data and wearables	• The demonstration of improved interface between machines and man through the use of wearable sensor data and current onsite data. • Application of data analytics to data from site workers towards ensuring employee wellbeing, efficiency and safety at a site and personal level.	• A step change in available data from multiple sources. • Improvement in productivity, employee wellbeing and safety. • Construction site layout design would be improved and site decision making supported by intelligent information. • Improved understanding of the impact of site work on employees leading to the identification of more efficient ways of working; targeted employee training and safer environments.
2	Collaborative platform model and data analytics	• Develop a novel collaborative “connected” platform as a single point of data collation. • Deploy established analytical tools to process data into meaningful knowledge to influence site design and employee safety on site in real time. • Provide context aware and localised processing of data enabled by the three phase use of building components as intelligent assets.	• This will lead to improved national records and measurement of performance on all construction sites. It will also enable holistic derivation of knowledge from multiple sites which will drive new strategies that improve worker’s productivity. • The data from national sites will also provide increased relevance to the data and could provide insights for better designing of man-machine interfaces. • Insights from increased levels of data would aid the development of sustainable and efficient business practices and solutions. • The three phase use of building components as intelligent assets will need the development of suitable edge device sensor packs. This approach will ensure that the lifecycle of construction parts are readily mapped from cradle to grave.
3	Video and sound processing digital twins	• Combine the latest video and sound signal processing technology to develop construction site ‘digital twins’.	• In creating a digital twin, the background signature of any site and surrounding areas can be recorded. This will provide the capability to identify anomalies that may be dangerous. • Partly constructed buildings will be able to signal hazard warnings and information about their current state to workers on their held or worn smart devices. • Digital twins will enable the possibility of: (1) tracking assets, (2) identifying assets (workers, machines, equipment, robots, parts etc) dependency on each other and potential for accidents and (3) controlling and utilizing a swarm of robots to aid in construction.

within construction activities, especially those involving supply chains, can benefit significantly from the introduction of digital technologies.

Furthermore, the smart worker concept is influencing the design of human computer/machine interfaces and brings a new level of onsite sensing to provide real-time updates on construction site state and its safety, as the construction progresses. Developments within the world of robotics are now being exploited to help develop new machinery for the production of modular buildings, thereby carrying over much of the process currently employed to manufacture highly customized consumer products. It is also the case that when used in the context of a connected BIM system, 4-D CAD models utilizing animated timelines can form the basis for a joint understanding of requirements between interested parties at various stages of a large construction project. The use of mixed reality with such models will also support onsite activities and ensure correct procedure and worker safety onsite.

In order to achieve the aforementioned, the Industry 4.0 pillar of “connectedness” underpinned by various communication standards and the industrial IoT will be required.

IX. CONCLUSION

From the analysis completed in this article, significant research gaps remain in the process of making the digital construction site a reality. The future of construction will rely on taking a “systems” view of existing and new digital technologies with their combined use in a connected holistic architecture. As a result, the Industry 4.0 technologies used in the future construction site will not work in isolation but will instead work together to resemble a complex cyber–physical system. The constituent technologies will be continuously shaped by reductions in device sizes, improved communication technology, increases in power density of batteries, and higher computational power in IoT edge devices.

Sensors, especially when utilized within wearable devices, can provide timely hazard alerts to workers. A potential new line of research involves the investigation of smart fabrics that when worn can be used to detect presence of chemicals and monitor the health of the worker. The use of wearables is particularly pertinent for highway construction workers who face additional hazards from moving traffic and associated exhaust fumes. It is also the case that sensors may be built into passive equipment associated with construction, such as cones, to provide safety and early warnings to both workers and drivers alike. CAD models are now more commonplace not just at the planning stages but also throughout the build process and beyond. With developments in both wireless communication hardware and associated communication protocols, the potential exists for real-time connected models of construction sites to provide full lifecycle decision-making support and perhaps in the future act as a monitoring dashboard for semi or fully automated construction processes. The three-phase use of building components as intelligent assets could provide a new real-time and context-aware stream of data for use within a digital twin environment and in communication to both workers and automated industrial processes. With the aid of increased processing speed, intelligent tools, smaller sensors, and reduced cost of data storage/transmission, machines and products should be enabled to communicate and learn from each other. The challenges and opportunities inherent in the implementation of Industry 4.0 in construction will provide scope for further exploration in the next five to ten years.

REFERENCES

[1] J. Maier, "Made Smarter Review," UK Department for Business, Energy and Industrial Strategy, 2017. Accessed: May 27, 2020. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/655570/20171027_MadeSmarter_FINAL_DIGITAL.pdf

[2] McKinsey Global Institute, "Reinventing construction through a productivity revolution," 2017. Accessed: May 27, 2020. [Online]. Available: https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/reinventing-construction-through-a-productivity-revolution

[3] F. Tao, J. Cheng, Q. Qi, M. Zhang, H. Zhang, and F. Sui, "Digital twin-driven product design, manufacturing and service with big data," *J. Adv. Manuf. Technol.*, vol. 94, no. 9/12, pp. 3563–3576, 2018.

[4] UK Government, Construction 2025. (2013). Accessed: May 27, 2020. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/210099/bis-13-955-construction-2025-industrial-strategy.pdf

[5] German Federal Government. (2016). The *New* High-Tech Strategy Innovations for Germany. Accessed: May 27, 2020. [Online]. Available: https://www.bmbf.de/pub/HTS_Broschuere_eng.pdf

[6] J. B. Yu, Y. Yu, L. N. Wang, Z. Yuan, and X. Ji, "The knowledge modeling system of ready-mixed concrete enterprise and artificial intelligence with ANN-GA for manufacturing production," *J. Intell. Manuf.*, vol. 27, no. 4, pp. 905–914, 2016.

[7] F. L. Zhang, H. B. Xiong, W. X. Shi, and X. Ou, "Structural health monitoring of Shanghai tower during different stages using a Bayesian approach," *Struct. Control Health Monit.*, vol. 23, no. 11, pp. 1366–1384, 2016.

[8] H. Son, C. Kim, and C. Kim, "Automated color model-based concrete detection in construction-site images by using machine learning algorithms," *J. Comput. Civil Eng.*, vol. 26, no. 3, pp. 421–433, 2011.

[9] A. Rashidi, M. H. Sigari, M. Maghiar, and D. Citrin, "An analogy between various machine-learning techniques for detecting construction materials in digital images," *KSCE J. Civil Eng.*, vol. 20, no. 4, pp. 1178–1188, 2016.

[10] O. Moselhi, and A. Alshibani, "Optimization of earthmoving operations in heavy civil engineering projects," *J. Construction Eng. Manage.*, vol. 135, no. 10, pp. 948–954, 2009.

[11] A. Asadi, M. Alsubaey, and C. Makatsoris, "A machine learning approach for predicting delays in construction logistics," *Int. J. Adv. Logistics*, vol. 4, no. 2, pp. 115–130, 2015.

[12] S. Bayram, M. E. Ocal, E. Laptali Oral, and C. D. Atis, "Comparison of multi-layer perceptron (MLP) and radial basis function (RBF) for construction cost estimation: The case of Turkey," *J. Civil Eng. Manage.*, vol. 22, no. 4, pp. 480–490, 2016.

[13] I. D. M. Aripin, E. M. A. Zawawi, and Z. Ismail, "Factors influencing the implementation of technologies behind Industry 4.0 in the Malaysian construction industry," *MATEC Web Conf.*, vol. 266, 2019. Art. no. 01006.

[14] P. Dallasega, E. Rauch, and C. Linder, "Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review," *Comput. Ind.*, vol. 99, pp. 205–225, 2018.

[15] I. Hager, A. Golonka, and R. Putanowicz, "3D printing of buildings and building components as the future of sustainable construction?" *Procedia Eng.*, vol. 151. pp. 292–299, 2016.

[16] B. García de Soto, I. Agustí-Juan, S. Joss, and J. Hunhevicz, "Implications of construction 4.0 to the workforce and organizational structures," *Int. J. Construction Manage.*, pp. 1–13, 2019.

[17] I. Paoletti, and E. Misayaka, "Adaptive manufacturing: A new perspective for construction industry," in *Back to 4.0: Rethinking the Digital Construction Industry*, Ciribini *et al.*, Eds., Maggioli, 2016, pp. 341–350.

[18] S. Zollmann, C. Hoppe, S. Kluckner, C. Poglitsch, H. Bischof, and G. Reitmayr, "Augmented reality for construction site monitoring and documentation," *Proc. IEEE*, vol. 102, no. 2, pp. 137–154, Feb. 2014.

[19] J. K. Whyte and T. Hartmann, "How digitizing building information transforms the built environment," *Building Res. Inf.*, vol. 45, no. 6, pp. 591–595. 2017.

[20] S. Zhang, K. Sulankivi, M. Kiviniemi, I. Romo, C. M. Eastman, and J. Teizer, "BIM-based fall hazard identification and prevention in construction safety planning," *Safety Sci.*, vol. 72, pp. 31–45, 2015.

[21] H. Malekitabar, A. Ardeshir, M. H. Sebt, and R. Stouffs, "Construction safety risk drivers: A BIM approach," *Safety Sci.*, vol. 82, pp. 445–455, 2016.

[22] C. S. Park, and H. J. Kim, "A framework for construction safety management and visualization system," *Automat. Construction*, vol. 33, pp. 95–103, 2013.

[23] X. Wang, P. E. Love, and P. R. Davis, "BIM+ AR: A framework of bringing BIM to construction site," in *Proc. Construction Res. Congr., Construction Challenges Flat World*, 2012, pp. 1175–1181.

[24] T. D. Oesterreich, and F. Teuteberg, "Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry," *Comput. Ind.*, vol. 83, pp. 121–139, 2016.

[25] X. Li, W. Yi, H. L. Chi, X. Wang, and A. P. Chan, "A critical review of virtual and augmented reality (VR/AR) applications in construction safety," *Automat. Construction*, vol. 86, pp. 150–162, 2018.

[26] B. Dave *et al.*, "Intelligent products: Shifting the production control logic in construction (with Lean and BIM)," in *Proc. 23rd Annu. Conf. Int. Group Lean Construction*, Perth, Australia, Jul. 29–31, 2015.

[27] B. Dave, A. Buda, A. Nurminen, and K. Främling, "A framework for integrating BIM and IoT through open standards," *Automat. Construction*, vol. 95, pp. 35–45, 2018.

[28] C. Boton, "Supporting constructability analysis meetings with immersive virtual reality-based collaborative BIM 4D simulation," *Automat. Construction*, vol. 96, pp. 1–15, 2018.

[29] T. Cheng, J. Teizer, G. C. Migliaccio, and U. C. Gatti, "Automated task-level activity analysis through fusion of real time location sensors and worker's thoracic posture data," *Automat. Construction*, vol. 29, pp. 24–39, 2013

[30] B.W. Jo, Y. S. Lee, R. M. A. Khan, J. H. Kim, and D. K. Kim, "Robust construction safety system (RCSS) for collision accidents prevention on construction sites," *Sensors*, vol. 19, no. 4, 2019, Art. no. 932.

[31] ATOS. (2017). Smart Fabrics White Paper. Accessed: May 27, 2020. [Online]. Available: https://atos.net/wp-content/uploads/2018/01/atos-smartfabric-white-paper-1.pdf

[32] J. Oyekan *et al.*, "A 3D immersive discrete event simulator for enabling prototyping of factory layouts," *Procedia CIRP*, vol. 38, pp. 63–67, 2015.

[33] C. Turner, W. Hutabarat, J. Oyekan, and A. Tiwari, "Discrete event simulation and virtual reality use in industry: New opportunities and future trends," *IEEE Trans. Human-Mach. Syst.*, vol. 46, no. 6, pp. 882–894, Dec. 2016.

[34] T. Delbrügger, L. T. Lenz, D. Losch, and J. Roßmann, "A navigation framework for digital twins of factories based on building information modeling," in *Proc. 22nd IEEE Int. Conf. Emer. Technol. Factory Automat.*, 2017, pp. 1–4.

[35] G. Uggla, "Connecting digital and physical representations through semantics and geometry," Doctoral dissertation, KTH Royal Institute of Technology, Stockholm, Sweden, 2019.

[36] S. Boschert, C. Heinrich, and R. Rosen, "Next generation digital twin," in *Proc. TMCE*, Las Palmas de Gran Canaria, Spain, 2018, pp. 209–218.

[37] H. Zhang, Q. Liu, X. Chen, D. Zhang, and J. Leng, "A digital twin-based approach for designing and multi-objective optimization of hollow glass production line," *IEEE Access*, vol. 5, pp. 26901–26911, 2017.

[38] EU. (2017). H2020 SafeLane Project. Accessed: May 27, 2020. [Online]. Available: https://cordis.europa.eu/result/rcn/150916_en.html

[39] D. Crawford, "Wireless sensors in traffic cones to protect workers," Eng. Technol., 2014. Accessed: May 27, 2020. [Online] Available: https://eandt.theiet.org/content/articles/2014/06/wireless-sensors-in-traffic-cones-to-protect-workers/

[40] SmartCone Inc. (2019). SmartCone, Accessed: May 27, 2020. [Online]. Available: https://thesmartcone.com

[41] J. Louis, and P. S. Dunston, "Integrating IoT into operational workflows for real-time and automated decision-making in repetitive construction operations," *Automat. Construction*, vol. 94, pp. 317–327, 2018.

[42] Y. Niu, W. Lu, K. Chen, G. G. Huang, and C. Anumba, "Smart construction objects," *J. Comput. Civil Eng.*, vol. 30, no. 4, 2015, Art. no. 04015070.

[43] J. P. Amezquita-Sanchez, M. Valtierra-Rodriguez, and H. Adeli, "Wireless smart sensors for monitoring the health condition of civil infrastructure," *Scientia Iranica*, vol. 25, no. 6. pp. 2913–2925, 2018.

[44] F. Maggi *et al.*, "A security evaluation of industrial radio remote controllers," in *International Conference on Detection of Intrusions and Malware, and Vulnerability Assessment*. Cham, Switzerland: Springer, 2019, pp. 133–153.

[45] I. Bisio, C. Garibotto, A. Grattarola, F. Lavagetto, and A. Sciarrone, "Exploiting context-aware capabilities over the internet of things for industry 4.0 applications," *IEEE Netw.*, vol. 32, no. 3, pp. 101–107, May/Jun. 2018.

[46] B. Edrington, B. Zhao, A. Hansel, M. Mori, and M. Fujishima, "Machine monitoring system based on MTConnect technology," *Procedia CIRP*, vol. 22. pp. 92–97, 2014.

[47] A. Koronios, D. Nastasie, V. Chanana, and A. Haider, "Integration through standards—An overview of international standards for engineering asset management," in *Proc. 4th Int. Conf. Condition Monit.*, Harrogate, U.K., 2007.

[48] R. Henßen and M. Schleipen, "Interoperability between OPC UA and AutomationML," *Procedia CIRP*, vol. 25, pp. 297–304, 2014.

[49] J. P. Liyanage, J. Lee, C. Emmanouilidis, and J. Ni, "Integrated e-Maintenance and intelligent maintenance systems," in *Handbook of Maintenance Management and Engineering*. Berlin, Germany: Springer, 2009, pp. 499–539.

[50] I. Grangel-González, L. Halilaj, G. Coskun, S. Auer, D. Collarana, and M. Hoffmeister, "Towards a semantic administrative shell for industry 4.0 components," in *Proc. IEEE 10th Int. Conf. Semantic Comput.*, 2016, pp. 230–237.

[51] M. R. Shahriar, S. N. Al Sunny, X. F. Liu, M. C. Leu, L. Hu, and N. T. Nguyen, "MTComm based virtualization and integration of physical machine operations with digital-twins in cyber-physical manufacturing cloud," in *Proc. 5th IEEE Int. Conf. Cyber Secur. Cloud Comput./4th IEEE Int. Conf. Edge Comput. Scalable Cloud*, 2018, pp. 46–51.

[52] R. Maskuriy, A. Selamat, K. N. Ali, P. Maresova and O. Krejcar, "Industry 4.0 for the construction industry—How ready is the industry?" *Appl. Sci.*, vol. 9, no. 14, 2019, Art. no. 2819.

[53] P. Dallasega, E. Rauch, and C. Linder, "Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review," *Comput. Ind.*, vol. 99, pp. 205–225, 2018.

[54] W. S. Alaloul, M. S. Liew, N. A. W. A. Zawawi, and I. B. Kennedy, "Industrial Revolution 4.0 in the construction industry: Challenges and opportunities for stakeholders," *Ain Shams Eng. J.*, vol. 11, no. 1, pp. 225–230, 2020.

[55] D. McFarlane, A. Parlikad, D. Pocock, S. Parsons, J. Schooling, and C. Jensen, "Intelligent infrastructure for tomorrow's assets: Guiding principles," ICE Guidance Paper. Institution of Civil Engineers, London, U.K. 2017.

[56] J. Oyekan, W. Hutabarat, C. Turner, C. Arnoult, and A. Tiwari, "Using Therbligs to embed intelligence in workpieces for digital assistive assembly," *J. Ambient Intell. Humanized Comput.*, vol. 11, pp. 2489–2503, 2020.

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