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Digital skin of the construction site

Smart sensor technologies towards the future smart construction site

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Abstract

Purpose – The future construction site will be pervasive, context aware and embedded with intelligence. The purpose of this paper is to explore and define the concept of the digital skin of the future smart construction site.

Design/methodology/approach – The paper provides a systematic and hierarchical classification of 114 articles from both industry and academia on the digital skin concept and evaluates them. The hierarchical classification is based on application areas relevant to construction, such as augmented reality, building information model-based visualisation, labour tracking, supply chain tracking, safety management, mobile equipment tracking and schedule and progress monitoring. Evaluations of the research papers were conducted based on three pillars: validation of technological feasibility, onsite application and user acceptance testing.

Findings – Technologies learned about in the literature review enabled the envisaging of the pervasive construction site of the future. The paper presents scenarios for the future context-aware construction site, including the construction worker, construction procurement management and future real-time safety management systems.

Originality/value – Based on the gaps identified by the review in the body of knowledge and on a broader analysis of technology diffusion, the paper highlights the research challenges to be overcome in the advent of digital skin. The paper recommends that researchers follow a coherent process for smart technology design, development and implementation in order to achieve this vision for the construction industry.

Keywords Information systems, Innovation, Technology, Construction, Information and communication technology (ICT) applications, Novel method

Paper type Literature review

1. Introduction

1.1 The context-aware pervasive construction site of the future

With the exponential rate of innovation in computing devices, communication technologies and technological applications, the world is rapidly developing and increasingly making use of smart technologies. This paradigm shift occurred from mobile computing to pervasive computing and then to smart technologies with embedded intelligence as explained below.

Mobile computing enables "connectivity any-where, any-time". This promising technology enables connectivity to be achieved without wires wherever and whenever users wish. More than a decade of extensive research has enabled the mobile computing paradigm (Satyanarayanan, 2001) to be shifted to a pervasive computing paradigm. Pervasive computing extends connectivity beyond "anywhere and anytime to on any device".

Pervasive computing is defined as "the physical world that is richly and invisibly interwoven with sensors, actuators, displays, and computational elements, embedded

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seamlessly in the everyday objects of our lives, and connected through a continuous network" (Weiser *et al.*, 1999). Pervasive computing also termed as ubiquitous computing envisages connectivity extending beyond traditional devices, such as personal computers, tablets or smart phones, to everyday devices. The notion of connectivity on any device imagines having chips embedded in devices ranging from clothing, tools and appliances to coffee mugs, and even the human body. For example, an ambitious version of the idea of a "cashless society" might aim to have a chip implanted in the human body as a form of biometric identification. Despite arguments about the extent to which technology should penetrate human life, recent trends in technology adoption provide evidence that the world is moving towards the connectivity of day-to-day devices with an infinite network of other devices, allowing them to connect to the internet, enabling the Internet of Things (IoT) (Gubbi *et al.*, 2013).

The next revolution of pervasive applications combines technologies such as wireless computing, voice recognition, internet capability and artificial intelligence (AI) to enable devices to adapt their behaviours to their physical environment in order to be smart (Gubbi *et al.*, 2013).

Hence, the connectivity of the future smart-pervasive era will be "any-where, any-time, on any-device with embedded intelligence". This fundamental aspect of such smart systems is also referred to as context awareness. Dey (2001) defines context awareness as follows: "A system is context aware if it uses context to provide relevant information and/or services to the user, where relevance depends on the user's task". Dey (2001) defines context as "Any information that can be used to characterise the situation of an entity". One of the most widely applied parameters in context-aware applications is "location"; the context-aware application is made location-aware.

Aligning the construction industry with these global technological trends, a new vision for the "construction site of the future" (Bowden, 2006) has emerged, characterised by Carbonari *et al.* (2011) by "real-time context awareness embedded in construction applications".

1.2 How far off is the future of the construction industry?

It is debatable how many years away the "construction site of the future" might be, particularly because the construction industry has not typically been pioneering in embracing technology when compared to other industries (Bowden, 2006; Ruddock, 2006; Navon and Sacks, 2007; Hosseini *et al.*, 2013; Edirisinghe, Blismas, Lingard and Wakefield, 2014).

While the construction industry faces the same barriers to technology adoption as any other industry, such as attitudes and people transformation for technology acceptance (Xu *et al.*, 2014), this industry's particular characteristics introduce unique challenges for implementing technology to its full potential. One such characteristic is the heterogeneity of construction sites. As Bowden *et al.* (2006) argue, construction projects have to deal with diverse and competing stakeholder groups from various disciplines, resulting in social complexity, and most of the time there are no long-term working relationships beyond the scope of a single project (Navon and Sacks, 2007). Often projects are executed by multiple units, and they can also be geographically dispersed. An additional complexity is introduced by the dynamicity of construction activities. Bowden *et al.* (2006) contrast this dynamicity, where "workers travel to the work", with the production line model, where "work travels to the workers". As a result, technology adoption is easier in the latter context because of the stable environment. Furthermore, each construction project is in some way unique, while also having societal and technical complexity in its environment.

Technologies designed for the construction industry need to cater for dynamic project conditions, widely dispersed construction activities, multi-level organisational structures, geographical and organisational proximity issues, construction workers' changing locations and so on. Studies concerned with these challenges, such as delivery of the right information to the right person at the right time and at the right place (Bowden *et al.*, 2006; Magdic *et al.*, 2004), are pertinent to discussions of context-aware pervasive applications.

However, with the realisation of the social and economic benefits of technology adoption for the construction industry, a large number of studies have been published in the recent past which seek to overcome these challenges. These benefits include cost and time savings, productivity improvements (Kang *et al.*, 2008; Shan *et al.*, 2012), the need for improved visualisation (Brandon and Kocatürk, 2009), globalisation through virtual teams (Vorakulpipat *et al.*, 2010), as well as quality enhancement, increased client satisfaction, competitive advantage, easier information exchange and various other value propositions for stakeholders (Eastman *et al.*, 2011) throughout the construction process (not only contractors, but also clients, architects, engineers and facility operators).

Generic information and communication technology (ICT) applications already appear in many areas of the construction industry. Such applications include automation of human resources and knowledge management, document classification (Al Qady and Kandil, 2014), digital engineering for labour productivity (Poirier *et al.*, 2015) and construction management data visualisation (Chiu and Russell, 2013). For the purposes of this paper, the critical review of the state-of-the-art research focuses on the pervasive or smart technologies which will form the context-aware pervasive construction site of the future. Sensor technology related to the future construction site is the focus of this paper, and post-construction and facility management is excluded. The terms "smart construction site" and "pervasive construction site" are used interchangeably throughout the paper to refer to the context-aware construction site of the future.

To the best knowledge of the author, there is no comprehensive review of recent research on this topic available, though there is as yet no agreed definition of the "context-aware future construction site". This paper tries to close these gaps. For example, the review by Vähä *et al.* (2013) is limited in a number of respects. First, it focuses on robotics and industrial automation and places little emphasis on undertaking a critical review of context-aware sensor technologies. Second, the technologies are reviewed based on the type of communication technology used. This paper, in contrast, argues that communication is only one aspect of the research topic. It is vital to also consider the applied elements of innovation and basic research. Hence, a more appropriate method by which to analyse the technologies is to consider their application on site and the problem that the research is trying to address, rather than focusing on the underlying communication technology. Third, it is vital to investigate the impact of the research in terms of the ability to apply the technologies in the construction industry.

The aim of this paper is to critically analyse the existing research gaps in the field of the context-aware future construction site and to provide a comprehensive review for the research community. The contributions of this paper are multi-fold. In spite of being a widely researched and strategically vital, "smart technologies", in the context of future construction applications, are loosely defined in the literature. First, this paper aims to fill this research gap by providing a coherent, high-level view and definition of the context-aware future construction site, referred to as the digital skin. Second, the paper provides a systematic review of the existing research that has contributed to the development of digital skin based on the technology readiness level (TRL) model (Mankins, 1995). This includes a classification and evaluation of relevant studies. The review methodology is discussed in greater detail in the next section. Third, based on the technologies currently available, the paper envisages scenarios for the future construction site in a number of application areas, such as procurement management, and construction worker and site safety management. Finally, based on the review findings and envisaged scenarios, this paper identifies research challenges yet to be addressed. This will provide useful insights for stakeholders for achieving the future smart construction site.

2. Research methodology

2.1 Data collection

Data for the review were collected from three main sources: academic/research articles; industry research and products; and patent documents. The search terms included "sensors and construction", "construction monitoring", "tracking in construction", "real time construction", "BIM", "augmented reality", "artificial intelligence", "monitoring", "locating", "localising", "construction assets" and "construction resources". To retrieve academic articles, initial Google Scholar and Scopus searches were conducted of academic and applied databases, and then an additional, specific search was conducted of four key journals in the field: *Automation in Construction*, *The Journal of Information Technology in Construction*, *The Journal of Construction Engineering and Management* and *The Journal of Computing in Civil Engineering*. Information about industry research and product development was also captured from publicly available information. However, the trajectories of research and development phases of some industry efforts were not fully available/traceable. An international patent search was also conducted, and only patents granted to date were collected. Any document management systems and web-based systems were excluded. Research on the pre- and post-construction phases was also excluded. The articles and web information were then archived. Altogether 114 articles were reviewed: 92 academic research articles, 16 industry research and development projects and 6 patents.

2.2 Review, classification and analysis

The comprehensive review process had two steps. First, content analysis of papers enabled identification of the elements of computer applications and software systems proposed in the study, as well as the aspects of construction to which these can be applied and the purpose and area of their application. This identification was based on the expertise of the researcher, who is an expert in the fields of ICT and smart technologies construction. Themes and sub-themes emerged, and these were recorded in a Microsoft Excel spread sheet. These themes were referred to as "application areas". To increase validity, an additional iteration of classification was conducted with an industry expert, which enabled the application areas to be revised. A two-level classification hierarchy was agreed upon.

Second, articles were selected for the detailed evaluation. Extended works were excluded. Some research studies had made a contribution to the digital skin research but only dealt with user/manual data entry systems. Such systems have no real-time element (Chen and Luo, 2014; Kim, Kim and Kim, 2013; Kim, Anderson, Lee and Hildreth, 2013) and so were excluded from detailed evaluation. Conceptual frameworks (14 articles) which did not deal with technology development were also excluded from the detailed evaluation. Ultimately, 72 articles were included in the detailed review.

Articles of the context-aware digital skin research were classified based on the aspects of construction to which it can be applied and the purpose. At the highest level, two application areas are identified: applications that use context-aware visualisation techniques, and real-time tracking applications. Applications that use context-aware visualisation techniques are further divided into two sub-classifications based on the type of visualisation technique: applications that use augmented reality (AR); and other modelling techniques such as building information modelling (BIM). Real-time tracking applications are divided into labour tracking, supply chain tracking, mobile equipment tracking, tracking for safety management, schedule and progress monitoring and visualisation-based tracking to improve safety.

These studies were evaluated according to the purpose of the research, the technology evaluations undertaken based on the TRL model (Mankins, 1995). These include prototyping, laboratory experiments or field trials as per the formal TRL model and also whether the studies that deal with the processes of adoption and acceptance of the technology in question were taken into account.

Widely used concepts such as smart technologies, pervasive, context-aware future construction site are loosely defined in the literature. This paper introduces the concept of digital skin in order to systematically define these concepts, which also helps setting the research boundaries. The next section defines the digital skin of future pervasive construction site.

3. "Digital skin" of future pervasive construction site

The digital skin of the future pervasive construction site is composed of a system of seamlessly networked sensors, actuators, displays and computational elements, with embedded intelligence and advanced digital applications, attached to various objects. These objects compose the digital skin and form connections to a network of other devices and, ultimately, to the internet. The digital skin is context aware, using various context parameters to provide relevant information and/or services to the user's tasks. This can include sensing various aspects of the physical environment (context parameters) and the construction site, allowing it to adapt its behaviours to changing dynamics through embedded intelligence. The digital skin is composed of three layers:

(1) Hardware: the hardware components of the digital skin include sensors, wearables, tags, smart phones, tablets, personal digital assistants, PCs or any object which has a chip or chips embedded in it for sensing a context parameter and for communication.

    Some examples include smart clothing, smart hard hats, smart safety glasses, tags attached to site equipment, mobile plants or materials or sensors placed on site to measure environmental conditions.

(2) Communication technologies: the objects in the digital skin combine various network technologies to communicate from dispersed locations across the site and ultimately over the internet. These technologies include Bluetooth and Zigbee (IEEE 802.15) forming a body area network (BAN), Wi-Fi (IEEE 802.11) forming a wireless local area network (WLAN), global positioning system (GPS) satellite communication, Cellular and Worldwide Interoperability for Microwave Access forming the wide area network (WAN) or metropolitan area networks and internet protocols (IPs) providing the connection to the internet.

    One example is the smart clothing to be worn by future construction workers that will have sensors to monitor workers' physiological conditions to improve their health and safety. These sensors communicate with each other through Bluetooth or Zigbee to form a BAN. The data are then communicated to the smartphone or site computer forming a WLAN. The data sent over the cellular network through short message service to any medical support service, when required, form a WAN. The data sent over the web to telemedicine services through the internet are the ultimate connection to the IP.

(3) Software, middleware or applications: these provide computation, analysis, storage, visualisation, analytics, AI and cloud computing capabilities to the digital skin, according to the application requirements. These make the system context aware and adaptive.

    In the case of a smart system to monitor the physiological conditions of construction workers, the system adapts itself to changing environmental conditions to provide general alerts. If the body/core or micro-climate temperature of the worker moves beyond acceptable thresholds, the system provides alerts of potential heat-stress or other conditions and related health hazards. The data analysis and embedded intelligence to change the system's behaviours are part of the digital skin. The digital skin is further explained and elaborated using selected scenarios later in the paper.

4. Review of context-aware digital skin research

This section presents a classification and review of the research studies on the digital skin of the future pervasive construction site. The studies illustrate diverse approaches within the scope of this paper.

4.1 Classification of the digital skin research

4.1.1 Applications that use context-aware information visualisation. AR-based applications. The effectiveness of onsite information systems such as BIM can be extended with real-time communication and real-time information. AR is defined as a combination of real and computer-generated scenes, where the "location" context parameter (set by real-world location) determines the content of the computer-generated scene. AR is also a technology that can bridge the gap between the digital and the real world (Meža, 2014). The recent special issue (2013) on "AR in Engineering and Construction" (AEC) in the journal *Automation in Construction* shows the need for, and interest in, research and innovation in the field. In another relevant study, Ibrahim and Kaka (2008) presented a review of photographic/imaging applications in construction. In addition, a 2013 survey (Chi *et al.*, 2013) identified future trends of AR in AEC applications, including field exploration through localisation, accessing field information using ubiquitous services and integrating with location-specific information. With the advancement and widespread of BIM in the construction industry, AR applications are becoming increasingly useful (Wang *et al.*, 2014; Park *et al.*, 2013; Meža *et al.*, 2014). The prototype developed by Wang *et al.* (2014) demonstrates the ability to use BIM + AR for visualisation/walking through, information retrieval, onsite assembly and way-finding based on the "location" context parameter. In a study by Wang *et al.* (2014), an AR prototype was developed to assist the installation of piping. Similarly, Meža *et al.* (2014) reviewed system functionality from a technical point of view. The prototype by Meža *et al.* (2014) was tested on the construction site of a 12-storey residential building. Park *et al.* (2013) proposed a framework for construction defect management using BIM and AR based on ontology. Although their study was limited to the conceptual, laboratory level, it proposed an innovative, real-time, location-based, proactive defect management mechanism.

Industry research and/or products have also come out recently which deliver contract-awareness for information visualisation. An AR smart helmet (DAQRI, 2017) has been developed for next-generation construction and is currently undergoing industry trials. The smart helmet, when integrated with sensor and imaging technology, can create a location-specific AR overview. Functions of the helmet include situational awareness through data visualisation, thermal vision, guided work instructions and remote expert assistance. The developers of the prototype helmet, which has already been tested in a number of sectors, are currently seeking trial opportunities in the construction industry. Furthermore, an AR-based mobile app has been developed (Dalux, 2017) and trialled in construction projects. Through the app, construction workers can view the physical environment in real time, allowing them to visualise and interact with it in various ways. Despite limited information on trials being publicly available (regarding whether it has been verified through developmental or operational evaluations and tests), the technology appears to be available on the market. Trimble (2017), in collaboration with Microsoft, is developing mixed-reality applications for the building and construction industry. Pilots of such applications have been conducted with AECOM (CIOB, 2016) on three construction projects in London, Hong Kong and Denver. Also, Kamat and Dong (2017) invented a visualisation method which blends real and virtual construction jobsite objects in a dynamic AR scene in real time. The steps of their process include capturing an image of a construction jobsite object through a depth-sensing device and colour camera, registering the location of those images in a common coordinate system, projecting geographic information system (GIS) and/or CAD data to generate the AR scene, and removing hidden surfaces. Evidence on applied investigation of this technology is yet to be reported.

No matter how fascinating the technology is, for it to be used to its full capacity it must be accepted by the end users. In order to clarify the social aspects of AR in *n*-dimensions (Edirisinghe and Zaslavsky, 2014), a more generic representation of context parameters has been proposed by Kim (2013). Kim (2013) specified three dimensions of context immersion in AR: communication, relationship and mobility.

BIM-based applications. A conceptual framework linking BIM-based AR to construction sites was proposed by Wang *et al.* (2012). In their study, Motamedi and Hammad (2009) proposed a conceptual framework of radio-frequency identification (RFID) tagging linked with BIM for progress monitoring of construction projects as well as for facility management research.

BIM has been studied for the purpose of linking onsite information and activities in various aspects of construction, such as scheduling (Kim, Kim and Kim, 2013; Kim, Anderson, Lee and Hildreth, 2013; Wang *et al.*, 2014), supply chain (Aram *et al.*, 2013) and quality assurance (Chen and Luo, 2014). While real-time context was not used in these studies, location was manually tracked in some of them (Kim, Kim and Kim, 2013; Kim, Anderson, Lee and Hildreth, 2013; Aram *et al.*, 2013). An industry experiment conducted with augmented drones to facility construction progress monitoring (Bentley Systems, 2016) was not live. Similarly, there is little evidence about real-time capability of the AI technology that spots health and safety breaches on site (CIOB, 2017d) even though it was trialled by a number of contractors. Because these studies were not intended to allow for real-time behaviour adaption, they are not relevant to the concept of context-aware digital skin and are therefore excluded from this review.

However, these studies include extensive useful onsite context parameters – information related to site activities, resources (labour, material, plant and equipment), durations, products and processes – giving them the potential to qualify as digital skin if they were to be extended with real-time context capture and adaption. For example, smart BIM (Heidari *et al.*, 2014), which is a prototype of real-time interaction and task performance linked with smart objects and BIM, can be considered part of digital skin. Another example is the iHelmet (Yeh *et al.*, 2012), which extends the safety helmet into a real-time information retrieval and projection device. An iPod and a projector are attached to the safety helmet of a worker in order to retrieve BIM information for the worker when their location is entered. This information is then projected onto a nearby surface. This work is also an example of the use of wearables on smart construction sites. Akinci *et al.* (2006) propose an innovative approach of using temperature-sensors-based 3D point cloud-based system for construction quality control. The detection algorithm was verified through as-designed and as-built model comparisons of four cases.

3D mobile mapping technology (GeoSLAM, 2017) based on simultaneous localisation and mapping with handheld scanners has been trialled in a complex renovation project in the USA. An accuracy of 2 cm was recorded, with a four and a half hour time to scan the case study site. A combination of hardware and a mobile app called Spike (IkeGPS, 2016) converts a smartphone into a laser rangefinder which is compatible with commercial BIM software. A laser rangefinder hardware device is clipped onto the smartphone and communicates with the phone using Bluetooth. This smartphone-based laser rangefinder is an industry product that allows real-time measurements to be captured on site. A BIM-aware location-based application has also been developed for mobile devices (Dharwada *et al.*, 2016), which includes the ability to display floor plans based on the device's location, representations of equipment, real-time status information and alerts about physical equipment based on the location of the equipment, as well as information from a number of onsite sensors for parameters such as air flow, temperature of air within the VAV box, temperature settings and humidity.

4.1.2 Real-time tracking applications. Various technologies have been used for the tracking and monitoring of context parameters (such as levels of certain resources) on site (Shen and Lu, 2012). The concept of fleet management to track vehicles was applied in a construction context by Naresh and Jahren (1997). They provided conceptual examples of a tracking system based on GPS and telecommunication satellite positioning systems. Jaselskis *et al.* (1995) conceptualised using RFID technology in the construction industry with a system for managing concrete processing and handling, cost coding for labour and equipment and materials control.

"Communication technologies" introduced in Section 3, such as RFID, Zigbee, Wi-Fi/WLAN, ultra wideband (UWB), GPS and ultrasound, are used in many real-time tracking applications. RFID has been applied to the supply chain, for tracking tools (Goodrum *et al.*, 2006), materials (Jaselskis and El-Misalami, 2003; Ergen *et al.*, 2007), for example. Zigbee has been used to track near-miss incidents (Wu *et al.*, 2010) and UWB has also been used to manage real-time safety information (Carbonari *et al.*, 2011); both of these studies serve the purpose of improving onsite health and safety. Andoh *et al.* (2012) proposed a conceptual framework for linking RFID and GPS technologies for tracking site resources. GPS-based tracking for site operations (Pradhananga and Teizer, 2013) and fusion methods to combine multiple technologies for labour tracking to monitor productivity (Cheng *et al.*, 2013), as well as ergonomic analysis of construction sites (Cheng *et al.*, 2012), have also been trialled.

Vision-based (Teizer and Vela, 2009; Park *et al.*, 2011; Yang *et al.*, 2012), motion capture (Han and Lee, 2013), image processing (Khosrowpour *et al.*, 2014; Soltani *et al.*, 2016; Tajeen and Zhu, 2014; Rebolj *et al.*, 2008; Chi *et al.*, 2009; Brilakis and Soibelman, 2008), stereo vision systems (Son and Kim, 2010), video streaming (Memarzadeh *et al.*, 2013; Yang *et al.*, 2010), computer vision (Roh *et al.*, 2011) and point cloud data processing technologies (Ray and Teizer, 2013) have also been applied in construction. Various sensor ontologies were evaluated based on the capability of the technologies to support capturing construction field data with data acquisition technologies (Gao *et al.*, 2012). These systems use a camera as the sensing "hardware", and context-aware adaptive "software" as introduced in Section 3.

The following sections discuss the use of various communication technologies to track parameters in real-time to cater for specific application requirements on site.

Labour tracking applications. Navon and Goldschmidt (2003) proposed a conceptual model for automated data collection technology to locate construction workers; this was later used by Sacks, Navon and Goldschmidt (2003) to test a prototype labour control model integrated with a building project model.

Khoury and Kamat (2009) evaluated three position-tracking technologies for user localisation in indoor construction environments: WLAN, UWB and indoor GPS positioning systems. The proposed indoor GPS system uses laser and infrared (IR) light. The precision of each system was evaluated and the technical criteria, logistical issues and costs were discussed. The authors concluded that decisions on technology should be based on important technical criteria such as calibration and line-of-sight, in addition to other logistical matters such as availability, the prevailing legal environment (e.g. permitted bandwidth) and the associated implementation cost. The testing in this study was conducted in a controlled environment.

Ubiquitous location tacking systems to deliver context-specific information have been proposed for construction sites using integrated WLAN and GPS as the base technologies, such as by Behzadan *et al.* (2008). The tracking application proposed by these authors can automatically switch between positioning technologies based on whether the user is indoors or outdoors. Despite the practical limitations imposed on construction workers by wearing bulky devices, the proposed project is a viable approach to delivering context-specific information based on the user's location on the construction site. The capability of the system to deliver context data was verified in a controlled environment by Yang *et al.* (2010), who used a video camera machine learning algorithm to track workers on site. They developed an algorithm to track multiple workers and tested it in an experimental set-up as well as two real-world site scenarios, though neither of these real-world sites was highly dynamic.

More recently, labour tracking concepts have been extended to the monitoring of productivity (Cheng *et al.*, 2013) and to ergonomic analysis of construction sites (Cheng *et al.*, 2012), which has health and safety implications. Cheng *et al.* (2013) proposed a system that automatically analyses workers' activities task-by-task. The system uses a combination of real-time location sensors and thoracic posture data to analyse worker's activities by encoding material handling, and idle and travel in various zones, including the work zone, storage zone and rest zone. Despite the fact that the experiments were conducted in a controlled environment, rather than a real-world setting, the technology seems promising. Similarly, Jiang *et al.* (2015) developed a labour consumption measurement system based on GPS. Their system processes location data to determine whether a labourer is active within the boundaries of a predefined construction region. This system has been applied in a large hydropower project. To achieve the same goals in an interior construction setting, a vision-based method using special sensors would be applicable. However, this would be a particularly challenging task as construction activities have a large range of intra-class variability, including varying sequences of body posture and time spent on each individual activity (Khosrowpour *et al.*, 2014).

Passive RFID tags were attached to the hard hats of construction workers to track when they entered or left a site (RFID Journal, 2011). Management was able to capture the identity of each worker through a tag linked to the worker's name, address and other details, such as the worker's employer and training history. This tracking solution appears to be an established industry product which is commercialised through a monthly service fee.

Cheng *et al.* (2012) used the real-time location sensors and thoracic posture data combination to analyse the ergonomics (Migliaccio *et al.*, 2012; Ray and Teizer, 2012) of construction workers with a view to detecting unsafe behaviour in materials handling. A Wi-Fi finger-printing-based localisation technique was tested for indoor tracking by RFID tagging workers' safety helmets (Woo *et al.*, 2011). An innovative, non-invasive, device-free detection and localisation technique has also been proposed for construction sites (Edirisinghe, Blismas, Lingard, Dias and Wakefield, 2014). This study proposed the use of Wi-Fi signal processing techniques to mitigate the multi-path effect caused by the movements of construction workers onsite, especially detecting when workers had entered hazardous zones.

A construction hard hat with attached electronic circuitry tracks workers and their activities on site for safety objectives (Hudgens and McDermott, 2009). The electronics are detected by radio-frequency sensors placed throughout the construction site, as long as the hats are in range. Once detected, the location of the hard hat is determined and personal information stored in its electronic circuitry is received by the sensor. The location and personal information is reported to a monitoring system that uses it to track personnel movements, to detect unauthorised activity and to generate reports.

Supply chain applications. Research has identified the supply chain as a critical element of the digital skin, relevant both for productivity and security reasons. Work on automating the supply chain began with the introduction of barcodes in the construction industry for various purposes such as quantity take-off, field material control, warehouse inventory and maintenance, issuing of tools and consumable material, timekeeping and cost engineering, purchasing and accounting and document control (Bell and McCullouch, 1988). Bernold (1990) reported on the use of barcodes for material management in construction; an approach developed in a yard control system. Since then, substantial research has been conducted on the tracking of material and tools; the most widely used technology for this purpose is RFID. Li *et al.* (2005) proposed combining barcode and GPS technologies for material and equipment tracking in order to reduce construction waste. Jaselskis and El-Misalami (2003) and Song *et al.* (2006) used RFID for material tracking, and Goodrum *et al.* (2006) used the same technology to track tools. Ergen *et al.* (2007) used combined RFID and GPS to locating precast concrete components on site. Jang and Skibniewski (2009) proposed asset tracking based on combined radio and ultrasound technologies. Accuracy assessments were conducted on UWB technology to track construction resources in indoor (Maalek and Sadeghpour, 2013) and harsh environments (Cheng *et al.*, 2011). Irizarry *et al.* (2013) integrated BIM with the GIS to enable tracking of supply chain status and to provide warnings to ensure the delivery of materials. Although the system was intended to automatically visualise the data in real time, data were entered manually in the case study. Recently, Montaser and Moselhi (2014) extended RFID technology to track workers and material non-invasively by analysing the signals using a signal processing technique called triangulation.

A mobile app tracks the material deliveries by calculating their volumes (CIOB, 2017c). A patented image processing technique (Boardman *et al.*, 2016) is used to estimate the measurements without the need for any additional hardware, unlike other specialised measurement techniques that require special equipment. Other than this, no information is available about the trials of the app in construction, even though it is available as a commercial product. A solution based on RFID tags has been used to record prefabricated units in Hong Kong (RFID Journal, 2013a). In addition to the benefits of tracking the components as they leave the factory and are installed on site, being incorporated into a new structure, the method also reportedly avoids onsite errors, ensuring quality.

Mobile equipment operation applications. An early study on the control of construction plant using GPS is by Roberts *et al.* (1999). This work proposed using GPS to automate a blade laser control system in a bulldozer. Sacks, Navon, Shapira and Brodetsky (2003) developed a conceptual roadmap for automated monitoring of construction equipment using GPS data to monitor concrete bucket loading and unloading operations. This was later field tested in crane operation (Sacks *et al.*, 2005). Oloufa *et al.* (2003) applied GPS-based tracking of vehicles on construction sites to avoid collision. Lu *et al.* (2007) proposed RFID-based tracking and positioning of construction vehicles by integrating GPS with a vehicle navigation technology called "dead reckoning" (DR). DR automatically supplanted the GPS when GPS signals were unavailable or unreliable.

Pradhananga and Teizer (2013) implemented a GPS-based tracking and analysis system for construction site operations. In addition to the speedy analysis of single-system equipment, their GPS-based approach allows proximity analysis (Ray and Teizer, 2012) of multiple sources, which is useful for determining risks on job-sites. The tracking applications of GPS would be particularly useful in situations where multiple mobile plants are in operation. In a study by Ray and Teizer (2013), the proximity of a skid steer and an excavator was tracked and analysed for an entire day. The authors later used laser scan data to generate a through-point cloud to test blind spot monitoring for construction equipment.

Lee *et al.* (2012) proposed a BIM-based tower crane navigation system for blind lifts. The system they developed shows the location of a lifted object in the context of a building and its surroundings using an imported BIM model and data collected through various sensors including a video camera. The experiments were conducted on the construction site of a research building on a university campus. The technology's acceptance was also evaluated using two aspects of the technology acceptance model (TAM) by Davis (1989): ease of use and usefulness.

Reader-based RFID tags were affixed to tools, materials and components during the construction of an oil refinery in Australia (RFID Journal, 2012). Although information is not available as to the type of RFID tag used, the trials provided some useful results and user perspectives about acceptance of the technology. The suggestions included reducing the number of readers and obstructions to construction traffic, and that the system ought to be made robust enough for harsh site conditions and extreme temperatures. RFID tags were piloted for machinery and equipment tracking by the North American Construction Group (RFID Journal, 2009). Handheld readers were used to detect pieces of equipment valued over $5,000. RFID-tagged equipment on geographically dispersed sites were located using Google Earth software. An Italian engineering and construction company tracked offshore equipment such as vessels, cranes, drilling rigs, steel pipe slings, shackles and buoys around the world (RFID Journal, 2010). A handheld reader was used to locate the tags, on which important data about the equipment had been stored, including inspection dates and insurance information.

While a tremendous number of studies have been conducted on vision-based video or photography analysis and image processing techniques for progress monitoring and scheduling (Fard and Peña-Mora, 2007; Azimi *et al.*, 2011), this paper focuses on sensor-based applications in line with the concept of digital skin. Costin *et al.* (2012) used RFID tags to track equipment, material and workers on a high-rise renovation project to provide activity and project status monitoring. Vision-based techniques were also applied to track equipment operation. Automated 2D detection of construction workers and equipment through onsite video streams was conducted by Memarzadeh *et al.* (2013). Tajeen and Zhu (2014) successfully applied computer vision techniques to distinguish five classes of construction equipment (excavators, loaders, dozers, rollers and backhoes).

Schedule and progress monitoring applications. Hendrickson and Rehak (1993) and Retik and Shapira (1999) were early researchers on the visualisation of site activities using real-time images. Retik and Shapira (1999) integrated site-related activities into the planning and scheduling of a construction project using virtual reality. Reinhardt *et al.* (2000) proposed a system architecture for construction progress monitoring. Cheng and Chen (2002) combined barcode and GIS technologies with video monitoring to develop an automated schedule monitoring system for precast building construction. Fard and Peña-Mora (2007) dealt with visualisation techniques for construction progress monitoring that are not automated. Their technique compared a model of the building "as-planned" with a photograph of the building "as-built". Lee and Peña-Mora (2006) analysed progress through a material-based detection technique and the generation of an occlusion-free photograph. Chin *et al.* (2008) integrated RFID and four-dimensional computer-aided design to assess progress on structural steel works in two real-world high-rise construction projects. In their research, Rebolj *et al.* (2008) developed an automated activity tracking system based on image recognition. A pilot implementation of their system was used in an industrial construction process. Shape recognition was used as the image processing technology in construction by Brilakis and Soibelman (2008). Son and Kim (2010) field trialled a stereo-vision-based automated progress monitoring system to model the structural components of steel buildings. In research by Roh *et al.* (2011), progress monitoring was undertaken through the visualisation and comparison of as-built photographs of the construction project to an as-planned 3D BIM, together with a walk-through feature. Virtual (as-planned) and real-world (as-built) domains were integrated in this research; however, the photographs of the as-built structure were captured manually. The focus of Yang *et al.* (2012) was tower crane activity, which they tracked through image processing of video surveillance camera data. Their system was tested in two construction scenarios: concrete pour cycles and material hoist cycles.

Drones were used to capture video footage to analyse construction progress in real time (MIT, 2015). The technology was trialled to monitor the activities on a number of construction sites. User acceptance of the technology and issues around privacy were not reported. A multi-screen AR system invented by Hsieh *et al.* (2016) was used to monitor construction processes on site. It was equipped with multiple touch display screens to aid decision making by separating public and private information for the project, so as to improve efficiency and reduce misunderstandings during the construction process. A method for monitoring construction progress through image processing was invented by Golparvar-Fard *et al.* (2015). In this method, photographs taken on site are used to construct a 3D "as-built" model, and this is compared with the "as-planned" model. The as-built model is overlaid on the as-planned model for joint visualisation to show progress towards completion of the structure. Progress is indicated with colour-coded changed and unchanged elements in red and green, respectively, using the D4AR modelling platform (Golparvar-Fard *et al.*, 2009).

Safety management applications. Every resource on a construction site introduces its own set of safety hazards and exposes safety risks. Advances in ICT allow for representation of and reasoning about construction context parameters for safety management, which is part of the concept of digital skin.

In Wu *et al.* (2010), a real-time tracking system was developed as a low-cost solution to track near-miss incidents. This system included ultrasonic transceivers for outdoor and indoor real-time location tracking, adopted sensors for environment surveillance and used RFID for access control as well as storage of safety information about workers, equipment and material and a wireless sensor network for data transmission. The sensor boards were equipped with light, noise, temperature and humidity sensors. Historical near-miss accidents were analysed based on typical accident cases, and features of construction sites and characteristics of near-miss accidents were also considered in the development of the system. Field trials were conducted in a multi-storey warehouse. The paper argued that a warehouse sufficiently simulates the environment on construction sites. However, it is arguable whether the dynamicity and practical limitations of a construction site, in terms of activities and processes, are similar to those of a warehouse, especially for the evaluation of near-miss incidents, even though they are structurally similar. Teizer *et al.* (2010) tested the same RFID technology on a clean-coal power plant construction site to track the proximity of construction workers and equipment operators as part of a safety alert system. A recent study by Teizer and Cheng (2015) used UWB and GPS sensor location data of workers, equipment and georeferenced hazard areas to automatically identify additional hazards and to analyse the spatial-temporal conflicts between workers and the identified hazards. Experiments were conducted in a laboratory environment as well as in the field on a live site.

With advances in wearable technologies in the wider pervasive environment, these devices are also emerging in the construction industry. Edirisinghe and Blismas (2015) propose an innovative approach using wearable technology and e-textiles to monitor the physiological parameters of construction workers in real-time to improve health and safety. The technological feasibility of the proposed system has been validated by a prototype system that monitors body temperature, detects heat-stress conditions of construction workers and generates early warnings. Similarly, Yi *et al.* (2016) propose using existing wearable technologies combined with an evaluation of perceived exertion to improve health and safety for workers in hot and humid environments. This system includes wearable wrist-bands for the workers and environmental sensors to generate warnings. In the experiments, GPS was used in the outdoor setting of a construction site.

A wearable kit was designed to improve the safety of construction workers by means of real-time tracking of context parameters, and this kit has passed the field trial phase (CIOB, 2017a). The collection of online equipment was designed to improve the safety of operatives in the field, as well as the ergonomics of working environments. The online operative kit/sleeve was designed to have multiple personal protective equipment (PPE) elements to suit the operational requirements of project partners. These elements include: a high-vis jacket equipped with sensors able to analyse the air; glasses with an integrated camera; and safety boots allowing geolocation.

The EskoVest is an upper body exoskeleton designed to improve the health and safety of construction workers (Eskobionics, 2017). This robotic vest enables construction workers to lift heavy objects while minimising their exposure to muscle strain and injury. This commercial product is ready to launch (CIOB, 2017b). More details about the wider adoption of the technology in the construction industry are yet to be reported, possibly due to the disruptive nature of the technology, which features lots of electronics and control systems and which may present challenges to do with worker training.

Kelm *et al.* (2013) used a novel application of RFID technology to improve safety. Low-cost RFID tags were attached to PPE which was then combined with personnel identification to check how well personnel were complying with PPE requirements and to provide users with timely feedback. Personnel entering a construction site through a site gate were informed of the safety process and procedures to follow.

SmartCap (2017) is a commercially available product designed for fatigue monitoring. The safety helmet has a headband that monitors brain activity to capture signs of fatigue. This identifies times of risk of microsleep – unintended episodes of loss of attention often caused by monotonous or repetitive tasks. Alerts are sent through a mobile app. Site testing has revealed a reduction in fatigue incidents, as well as technological, social and policy challenges around wider adoption, including training workforces with limited literacy, calibration issues due to staff turnover and policy requirements due to union presence.

A ubiquitous sensor network (USN) was prototyped to monitor safety during concrete placement in a study by Moon *et al.* (2015). The system combined multiple technologies, such as sensors, wireless networking, safety monitoring applications and an independent power supply. The sensors collect context parameters such as distance, strain, weight and inclination. The safety manager in the site office can oversee the safety of concrete formwork and be assured that the construction operation is being safely executed through a web interface, smart phone and/or a smart glasses application. An independent power supply is used for USN technology to address the energy challenge which is common in wireless devices. The technology was tested in an onsite case study of concrete column construction. An RFID-based solution was used to automate safety and access management on site (RFID Journal, 2013b). Workers were given photo ID cards with built-in passive RFID tags linked with their individual details. A zone-based site access system based on safety training was also implemented. The RFID-based apparatus was proposed for mobile equipment to ensure the safety of workers in proximity. The apparatus is composed of an article of clothing wearable by the workers (clothing, a vest or a hard-hat) fitted with an RFID tag with an antenna. A second sensor is mounted on the mobile machine to detect the proximity of the RFID tags (Dasilva and Shervey, 2012). The plurality of directional antennas each corresponding to a danger zone sends and receives signals to and from the RFID tags within each zone.

Visualisation-based tracking to applications to improve safety. Some research combined tracking with digital engineering or visualisation for the purpose of improving safety. While serving the purpose of safety management, these technologies are also linked with visualisation. Hence, they are categorised separately.

Early work in this area included a system implemented to automatically monitor fall hazards through guardrail analysis (Navon and Kolton, 2006). The automated model identified fall hazards during scheduled activities through sensors which monitored the existing protective measures in real-time and warnings were generated accordingly. The proposed technique was implemented in a prototype for one kind of protective measure (guardrails) and tested onsite in an ongoing project where use feedback was also tracked. In a later study, Lee *et al.* (2009) developed a monitoring system based on ultrasonic and IR sensors combined with a wireless telecommunication system to detect fall accidents. The effectiveness of this system was evaluated on a real construction site. Real-time location data collection and visualisation technology were applied in construction safety and activity monitoring by Cheng and Teizer (2013) using crane lifting as a case study.

Park and Kim (2013) developed a prototype of a safety management and visualisation system with BIM, location tracking and game technologies. A prototype system has been developed and tested, based on an illustrative accident scenario. Once the safety risks are registered by the system during inspections, they are visualised in real time. Safety education can be facilitated through a question-and-answer-based game. This system was evaluated in a case study. A prototype for safety education was implemented for pipe shaft opening. This prototype was evaluated by construction workers, safety managers, construction managers and trade leaders on three criteria: identifying risk before work execution, increasing comprehension of accident risk and real-time communication.

The CoSMoS system (Riaz *et al.*, 2014) is a prototype developed to visualise the environmental temperature of confined spaces through real-time sensor data to improve safety. The prototype deploys two TelosB (Levis *et al.*, 2005) sensor motes in two confined spaces. Sensor data are visualised in the BIM in real time and the system generates warnings accordingly. CoSMoS is an example of a context-aware pervasive system that can adapt to its environmental context. The study reported that the accuracy of sensor data is a major challenge. The prototype was used to monitor confined space using only two sensor nodes. Industry feedback was captured in a focus group with contractors, researchers and consultants. The system's effectiveness, proactiveness, practicality, usability, financial feasibility, potential for future improvements, benefits and implementation barriers were evaluated.

Zhang *et al.* (2015) developed a prototype of automated workspace visualisation in BIM, using a remote sensing approach for activity-level construction site planning that can proactively improve construction safety. The system senses location data through a GPS attached to the hard hats of workers, and gives an approximation of the workspace to detect potential workspace conflicts among competing work crews or between material lifting equipment. Images from both a video camera and an unmanned aerial vehicle were also analysed. The prototype was trialled on a real site for three days during concrete column construction activities.

Carbonari *et al.* (2011) used UWB-based position tracking to implement virtual fencing to improve safety. The system puts in place a safety policy that generates warnings to prevent workers accessing hazardous areas (where the spatial coordinates of the area are predefined), such as where there is a high likelihood of objects falling from overhead. The prototype was tested under laboratory conditions as well as in the field.

Future construction site safety education is also part of digital skin. For example, in a study by Teizer *et al.* (2013), safety training for steel workers was conducted using real-time location tracking data visualisation technologies, putting the system to the test in the construction worker education and training environment.

4.2 Evaluation of the digital skin research

4.2.1 Research areas and technology readiness level. The objective of research studies in smart technologies for construction is: to solve an immediate problem; to solve progressive problems using a reflective process; or to ultimately translate the basic research into applied research. Hence, the above research studies were reviewed based on their approach to technology validation and applied research, with a focus on attempts to apply research to practice (RtP).

The technologies were evaluated based on TRLs (Mankins, 1995). The following descriptions of each level of technology readiness were used:

- Level 1: scientific research begins to be translated into applied research.
- Level 2: once basic principles are observed, practical applications are formulated through analytic studies.
- Level 3: active research and development is initiated to validate the research concept. The activities include analytical studies, and/or laboratory studies as part of knowledge production.
- Level 4: applied investigation begins. The activities include validating the functions in a controlled environment, such as a test bed, laboratory or through a scenario model.
- Level 5: prototypes of basic technological components are integrated for testing in a simulated environment, either in a laboratory or (through data collected from a) case study.
- Level 6: development captures the operational requirements. The prototype is qualified in an operational set-up representing a near-desired configuration. Activities include testing of the qualified prototype in a representative construction site set-up, and/or field tests.
- Level 7: full scaled-up system with all operational requirements met. The system, at planned operational level, is demonstrated in multiple operational environments to verify generalisability.
- Level 8: product commercialisation begins. The technology is proven to function in its final form under any operational environment, and is verified through developmental testing.
- Level 9: industrial system is launched/deployed in an operational set-up, and is verified through operational evaluations and tests.

The studies were analysed based on elements such as proofs of concept, laboratory experiments, trials or tests conducted during the prototype stage, real construction site tests, and tests to evaluate users' technology acceptance were also considered in the evaluation of research studies.

Table I summarises each of these levels used in the evaluation process. The table also summarises the three technological elements: hardware; communication technologies; and software, middleware or applications introduced to define digital skin in Section 3 against each study/article.

Table I. Summary of technology readiness level and digital skin characteristics of research studies

Technology readiness level (TRL)	Classification of TRL and characteristics of digital skin of each study/article				
Pre-concept refinement or knowledge production					
(1) Basic principles of concept/scientific research	Khoury and Kamat (2009), evaluation (WLAN, UWB, GPS)				
(2) Formulation of technology concept and/or application	Fard and Peña-Mora (2007), scheduling (images)				
(3) Proof of concept	Hsieh *et al.* (2016), monitor processes (AR)	Kamat and Dong (2017), AR object mapping	Roberts *et al.* (1999), plant control (GPS)	CIOB (2017c), tracks material volumes	CIOB (2017a), wearable kit for safety
	Edirisinghe, Blismas, Lingard, Dias and Wakefield (2014), non-invasive localisation (Wi-Fi)	Rebolj *et al.* (2008), activity tracking (images recognition)	Trimble (2017), mixed-reality applications	Navon and Kolton (2006), fall hazards (sensors and guardrail analysis)	Sacks *et al.* (2005), labour tracking (building models)
	Cheng and Chen (2002), monitor schedule (GIS, barcode, video)	GeoSLAM (2017), 3D mobile mapping technology with handheld scanners	Yi *et al.* (2016), evaluate perceived exertion (sensors)	MIT (2015), drones to capture progress	Golparvar-Fard *et al.* (2015), monitor processes (image)
	Jang and Skibniewski (2009), track assets (radio and ultrasound)	Dharwada *et al.* (2016), BIM-aware mobile app	Edirisinghe and Blismas (2015), monitor workers' parameters (E-textiles)	Hudgens and McDermott (2009), hard hat tracks worker activities	Akinci *et al.* (2006), quality control (sensors and point cloud)
		Dasilva and Shervey (2012), safety management (RFID)			
Applied investigation					
(4) Functional validation in a laboratory environment or test bed or scenarios	Park *et al.* (2011), track resources (image processing)	Montaser and Moselhi (2014), track workers/material (RFID)	Riaz *et al.* (2014)[c], visualise envi. temp. (Zigbee)	Moon *et al.* (2015), monitor safety (sensors)	
	Zhang *et al.* (2015), workspace visualisation (BIM)	Irizarry *et al.* (2013), supply chain tracking (RFID)	Yeh *et al.* (2012), information retrieval (hardware and BIM)	Song *et al.* (2006), material tracking (RFID)	

(*continued*)

Table I.

Technology readiness level (TRL)	Classification of TRL and characteristics of digital skin of each study/article				
	Maalek and Sadeghpour (2013), indoor resource tracking (UWB)	Yang *et al.* (2010), worker tracking (video, m/c learning)	Yang *et al.* (2012), tower crane activity tracking (video processing)	Bernold (1990), material management (barcodes)	
	Tajeen and Zhu (2014), equipment recognition (image processing)	Memarzadeh *et al.* (2013), workers and equipment detection (video streaming)	Khosrowpour *et al.* (2014), activity analysis (image processing)	Brilakis and Soibelman (2008), shape recognition (image processing)	
(5) Prototype in a simulated environment/ case study	Behzadan *et al.* (2008), context delivery (WLAN + GPS)	Cheng *et al.* (2012), ergonomic analysis (location, posture data)	Wang *et al.* (2014), visualisation (BIM, AR)	Goodrum *et al.* (2006), tool tracking (RFID)	
	Cheng *et al.* (2011), resource tracking in hash environment (UWB)	Yeh *et al.* (2012), information retrieval (iPod, a projector, BIM)	Sacks, Navon, and Goldschmidt (2003), labour tracking	Retik and Shapira (1999), activity visualisation	
	Son and Kim (2010), monitor progress (vision-based)	Carbonari *et al.* (2011), position tracking (UWB + virtual fence)	Park & Kim (2013)[b], safety management (BIM)	Heidari *et al.* (2014), real-time interaction (sensors + BIM)	Cheng *et al.* (2013), activity analysis (location, posture data)
	Teizer *et al.* (2013)[d], safety training (tracking, visualisation)	Roh *et al.* (2011), progress monitoring (image analysis, BIM)	Lee *et al.* (2009), fall detection (IR and ultrasonic)	Ergen *et al.* (2007), track components (RFID and GPS)	
	Teizer *et al.* (2010), proximity – workers/equipment (RFID)	Jaselskis and Misalami (2003), material tracking (RFID)	Oloufa *et al.* (2003), collision tracking (GPS)	Wu *et al.* (2010), track near-misses (ultrasonic and RFID)	
Development and operations					
(6) Qualified prototype demonstrating critical functionality in a relevant operational environment	Meža *et al.* (2014), AR task assisting (AR)	Pradhananga and Teizer (2013), track operations (GPS)	Kelm *et al.* (2013), monitor workers' PPE compliance (RFID)	Chin *et al.* (2008), monitor progress (RFID, 4D CAD)	Cheng and Teizer (2013), monitor activities (images)
	DAQRI (2017), AR smart helmet				Woo *et al.* (2011), track indoor workers (RFID)

(continued)

Technology readiness level (TRL)	Classification of TRL and characteristics of digital skin of each study/article				
	Lee *et al.* (2012),[a] positioning tower crane (BIM)	Jiang *et al.* (2015), labour consumption (GPS)	Costin *et al.* (2012),[e] monitor status (RFID)	RFID Journal (2013b), automate safety and access management	Teizer and Cheng (2015), hazard identification (UWB and GPS)
		RFID Journal (2012),[a] components tracking	RFID Journal (2009), equipment tracking	RFID Journal (2010), track offshore equipment	RFID Journal (2013a), track prefabricated units
(7) Full, scaled-up system demonstration (pre-product with all requirements) in an appropriate generalisation of real or operational environment	Eskobionics (2017), upper body exoskeleton minimising exposure to muscle strain and injury				
Industrial product					
(8) General product or technology completed and qualified through tests	Dalux (2017), AR-based mobile app	IkeGPS (2016), mobile app-based laser rangefinder			
(9) Industrial technology proven through successful deployment in an operational setting	RFID Journal (2011), hard hats to track workers	SmartCap (2017), fatigue monitoring hard hat			

Notes: [a]Lee *et al.* (2012) and RFID Journal (2012) evaluated technology acceptance. Lee *et al.* (2012) used TAM to evaluate; [b]Park and Kim (2013) evaluated a prototype through different stakeholders; [c]Riaz *et al.* (2014) sought feedback in a focus group; [d]Teizer *et al.* (2013) surveyed participants; [e]Costin *et al.* (2012) conducted a brief evaluation, but not a systematic one

Table I.

4.2.2 Distribution of research areas. Figure 1 shows the distribution of research efforts on digital skin. Research into tracking applications represents more than three quarters of overall research, whereas information visualisation is underrepresented. At the sub-research area level, a plurality of the papers (approximately 19.4 per cent) was published in the area of "construction equipment tracking". The second most popular research area was construction "schedule tracking and progress monitoring" with 17.5 per cent of papers. Visualisation for safety research made up the smallest percentage, 8.7 per cent. The other research areas did not show much deviation from their interests: AR (10.7 per cent), BIM apps (11.6 per cent), safety management (12.7 per cent), supply chain racking (14.6 per cent) and labour tracking (15.5 per cent).

Given the rapid pace of technology development, the year of publication was also taken into account. The articles in various research areas were analysed based on the year of publications.

Figure 2 shows the distribution of articles in various research areas over the years. Figure 3 illustrates further analysis of research interests based on main and sub-area clusters. Even though early concepts of digital skin research (particularly tracking applications in construction) were published in the decade between the late 1980s and late 1990s, a significant research interest can also be observed in the last decade (since 2007)

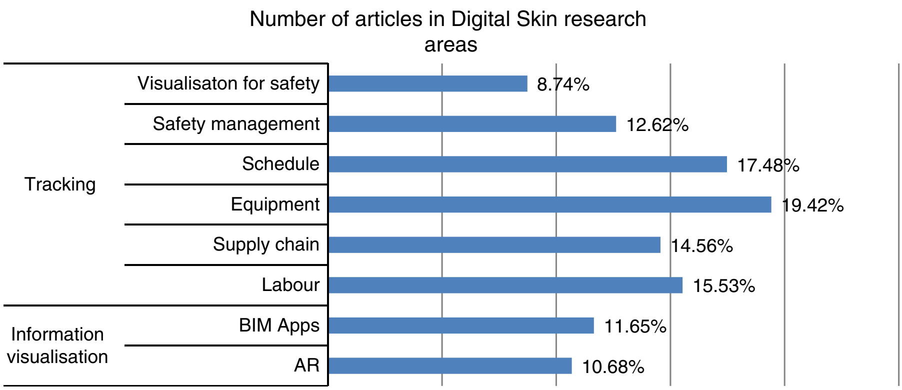

Figure 1.
Distribution of research efforts on digital skin

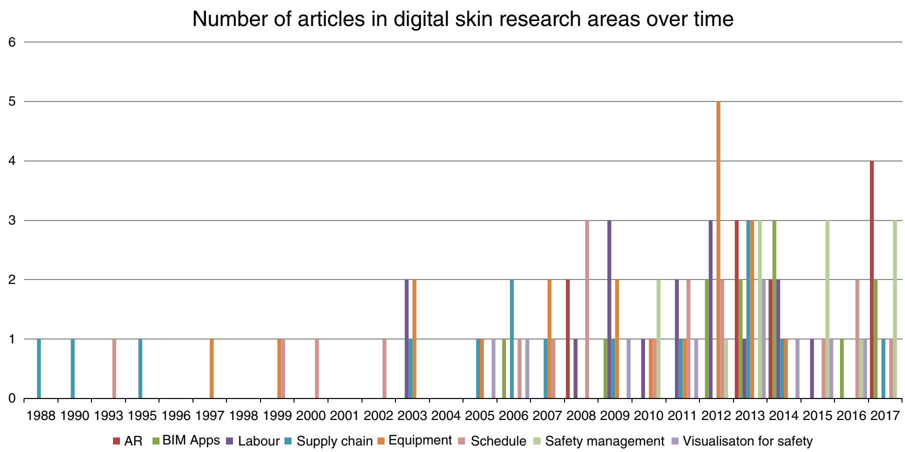

Figure 2.
Number of articles in sub-research areas over time

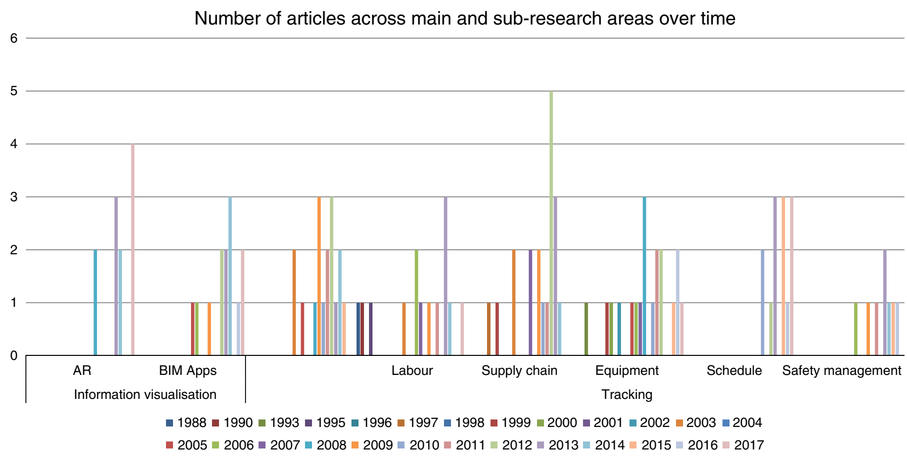

Figure 3. Number of articles in main and sub-research areas over time

based on emerging technologies. Construction resource tracking, including labour, supply chain and equipment tracking, has saw its peak number of publications in the period 2009–2013. It can also be observed that safety research related to digital skin (both tracking and visualisation for safety) and information visualisation research in general (both AR and BIM applications) have gained momentum more recently, which also explains the lesser overall contribution of these areas in Figure 1.

4.3 Findings from the review of digital skin research

The analysis of the literature through technology readiness in Section 4.2.1 and distribution of research in Section 4.2.2 revealed the following:

- Technology feasibility validation: most of the studies validated the feasibility of the technology in question through prototype testing, laboratory experiments, pilot studies, proofs of concept or experiments in controlled environments. However, the majority of studies were limited to prototype experiments to verify capability and reliability. Only a few studies followed the sequential steps outlined in the TRLs described above. For example, Pradhananga and Teizer (2013) and Teizer and Cheng (2015) tested the relevant technology in a controlled environment prior to conducting live site trials.
- Technology application on site: only some studies trialled their technology on site. Some of the studies involved quasi-site experiments, in which the site experiments were done in a controlled environment. Although these were termed "site testing" they were not classified as "site trialled". This paper argues that while it is essential to validate the feasibility of technology, it is paramount that its applicability be validated to the industry through onsite testing. Real sites introduce a range of practical limitations and issues due to their unique, individual environmental challenges and dynamicity, meaning that their development and operational needs (Mankins, 1995) can only be captured in the real-world setting. Reliability (Cheng *et al.*, 2013), robustness of the system (Yi *et al.*, 2016) and the capabilities of the hardware and software (Meža *et al.*, 2014) can also be validated by applying those technologies on site.
- Technology readiness or RtP: few industry research projects or products (with the little information publicly available on full R&D and product development and testing protocols) claimed that they were concentrated at the industrial product phase

(stages 7, 8 and 9 of the TRL model, meaning "full, scaled-up system demonstration (pre-product with all requirements) in an appropriate generalisation of real or operational environment", "general product or technology completed and qualified through tests" and "industrial technology proven through successful deployment in an operational setting"). None of the academic research either reached stage 7 (a full, scaled-up system demonstration to verify generalisability and system development for full operational needs) or the industrial product stage. It is acknowledged that studies can be in the process of transforming research into practice and that the process may yet to be reported.

- User acceptance tests for wider technology adoption: very few of the research studies/products considered the human element of technology acceptance. It is vital to consider motivators, benefits and barriers to adoption when evaluating technologies so that those technologies can be used on future construction sites to their full potential. These should be evaluated in both their technological and non-technological aspects to cover the spectrum of social, economic and policy dimensions.
- Emerging research areas: safety research related to digital skin (in both tracking and visualisation), and information visualisation research in general (both AR and BIM applications) have gained momentum in the last five years. This can be explained by the recent maturation of BIM technology and the recent prioritisation of safety research in construction due to the poor safety performance of the sector.
- Distribution of research efforts: tracking applications making up the majority of research interest can be explained by the maturity and availability of some of technologies (RFID, for example). The appearance of new, emerging technologies (e.g. IoT and wearables) was reported mostly to be in the early stages of TRL. From a research sub-area point of view, it is noteworthy that the research interests are not skewed towards a particular sub-area but represent a reasonably good balance.
- Lack of wider adoption of established research areas: construction resource tracking, including labour, supply chain and equipment tracking, has recorded its peak number of publications in the period 2009–2013, which can be explained by the little attention given to user acceptance tests. It is noted that industry research took over in these areas to some extent, but wider acceptance has been slow, even in the established research areas, due to multi-dimensional challenges as well as a lack of standardisation.

As described above, some of these innovations and technologies are in the early stages of the development process. A detailed discussion of these findings, the challenges for their use at full potential and the road ahead are provided in Section 6. Despite their being in the early stages, these research projects/technologies bring novel theoretical, methodological and/or empirical perspectives of expertise to drive innovation in construction towards the vision of the "construction site of the future" (Bowden *et al.*, 2006; Carbonari *et al.*, 2011). The next section addresses scenarios for the future smart construction site based on these pockets of research from the literature review.

5. Future construction sites

5.1 The future construction worker

It is envisaged that the future construction worker who is part of the digital skin of the context-aware future construction site will wear smart wearables. These include e-textiles, such as smart safety vests (Edirisinghe and Blismas, 2015), smart hard hats (SmartCap, 2017;

DAQRI, 2017; Yeh *et al.*, 2012; Zhang *et al.*, 2015; RFID Journal, 2011; Hudgens and McDermott, 2009), smart glasses, a wearable kit that can be customised according to a specific industrial need (CIOB, 2017a) and even an upper body exoskeleton for certain tasks to minimise exposure to muscle strain, injuries and musculoskeletal disorders.

5.1.1 Wearing smart e-textiles. Figure 4 illustrates the future construction worker, who will wear smart clothing with sensors embedded to monitor their physiological condition (Edirisinghe and Blismas, 2015). The sensors monitor context parameters such as body temperature, blood pressure, pulse rate, muscle strain, motion, electrocardiogram data or any other bio-medical criteria using various bio-medical pads. The system components communicate with each other, forming a BAN. They also update the data on the worker's smart phone, or the computer in the site office to enable management to visualise any situation that needs attention or a change to work procedures or processes.

Emergency services or medical support services will be alerted of unacceptable conditions should they arise. The data will also to be linked with telemedicine services. These external connections will be through the cellular network or the internet.

5.1.2 Wearing a smart hard hat. The hard hat of the worker will have a GPS attached to it (Zhang *et al.*, 2015) or RFID tags attached to it (RFID Journal, 2011) that can give an approximation of the (outdoor) workplace to detect any conflicts and hazards due to interaction with other trades/workgroups. Workers' tasks will be automatically analysed and productivity will be updated in the system (Cheng *et al.*, 2013). Any health and safety hazards related to ergonomics (Migliaccio *et al.*, 2012) or fatigue (SmartCap, 2017) will also alert the appropriate service, similar to the monitoring of physiological parameters discussed above. To improve health and safety in countries or organisations where privacy policies restrict tracking workers by tagging them, workers will instead be anonymously tracked to detect when they access hazardous areas (Kelm *et al.*, 2013; Edirisinghe, Blismas, Lingard, Dias and Wakefield, 2014; RFID Journal, 2011).

5.1.3 Wearing smart safety glasses. The smart glasses the worker wears will be able to visualise data. As Yeh *et al.* (2012) propose, future site workers will retrieve real-time information including BIM automatically. It is envisaged that future research will consider the various methods (such as rendering) by which BIM might be retrieved and displayed in

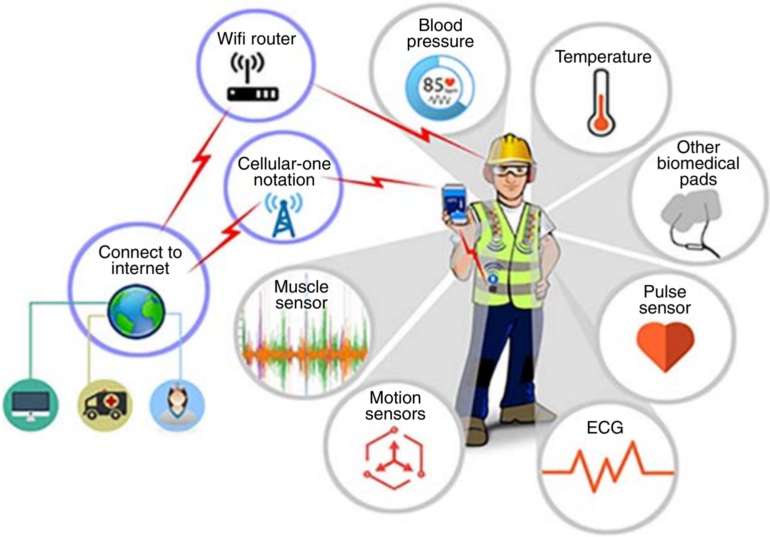

Figure 4. The future construction worker

the smart glasses. The data will be projected onto the smart glasses. The workers will receive activity-level site planning from project managers about day-to-day activities that will be visualised (Zhang *et al.*, 2015) on the smart glasses. The workers will also be able to watch safety training refreshers linked with BIM (Park and Kim, 2013) on the smart glasses when they wish. Alternatively, smart glasses can be integrated into the helmet, enabling an AR view (DAQRI, 2017), with AR-based smart phone apps also integrated (Delux, 2017).

5.2 Future construction procurement and project management

Figure 5 illustrates the supply chain of the future construction site. The digital skin extends beyond the geographical space of the construction site to the very origin of the supply chain: the raw materials. The currently fragmented and highly dynamic construction industry supply chain will, in the future, be more robust and more productive, with real-time information retrieval and dissemination, structured and efficient communication and embedded intelligence.

Tools and components on the construction site will carry tags such as RFID (Goodrum *et al.*, 2006; RFID Journal, 2012) including prefabricated units (RFID Journal, 2013a) and will be linked with associated work procedures to achieve productivity gains. These components with complex operating procedures will display a video on the workers' smart glasses once the tool's barcode is scanned by the worker. Materials will have tags (Jaselskis and El-Misalami, 2003) so that they can be tracked from manufacturing to distribution to transportation and then onsite. Visual representations of the context parameters related to material on site will enhance resource monitoring. Onsite material (including raw material usage through sensors as illustrated in Figure 5) tracking will also be non-invasive (Montaser and Moselhi, 2014). The volumes of onsite material will be tracked by scanning

Figure 5.
Future construction procurement and project management

technologies implemented through a smart device app (CIOB, 2017c) or by proximity or RFID sensor technology.

Site scheduling visualised on BIM will be linked with material consumption and auto-updated in the system for progress monitoring (planned vs actual material consumption) for better project schedule control. An "as-built" model will be digitised using smart technologies (Hsieh *et al.*, 2016; GeoSLAM, 2017), smart phones (IkeGPS, 2016) or even drones (MIT, 2015). Object mapping (Kamat and Dong, 2017), and image processing techniques (Golparvar-Fard *et al.*, 2015) will marry the real and augmented worlds to compare the as-built model with the as-planned model, giving workers and project managers an ultimate mixed-reality experiences on site (Trimble, 2017; Dharwada *et al.*, 2016). Life cycle tracking of the installed components (such as heating ventilation and air conditions-HVAC system as illustrated in Figure 5) will be enabled though the BIM model.

5.3 Future construction site safety management

Globally, the construction industry performs poorly in terms of its safety record. Future context-aware construction sites will have safety management with embedded intelligence as an integral part. The safety management system will have various objects which are part of the digital skin onsite jointly adapting to varying hazardous conditions automatically and detecting hazards proactively. Sensor technologies embedded in PPE will work together with sensors mounted on site (Dasilva and Shervey, 2012), or with RFID tags (RFID Journal, 2011) to detect workers' entry to hazardous zones or their proximity to mobile plants.

5.3.1 Plant operation. A major part of health and safety management is dedicated to plant and equipment onsite which have the potential to cause severe accidents with severe consequences. Figure 6 illustrates the future construction site's fixed and mobile plant operation. As illustrated in the figure, the plant onsite will carry various tags (RFID Journal, 2009, 2010). BIM-based mobile or fixed tower crane operation (Lee *et al.*, 2012), for example,

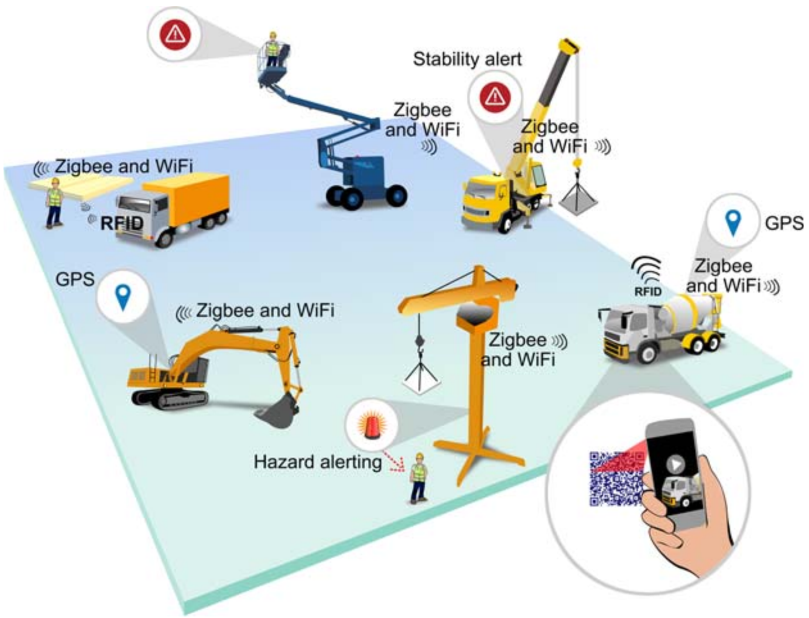

Figure 6.
Future construction site mobile plant operations

takes location data into the system to ensure safe operation. In addition, proximity analysis between multiple mobile plants (Pradhananga and Teizer, 2013) or between mobile plant and workers will be part of the digital skin. Similarly to the future management of tools, complex mobile plant operation and related work procedures will be digitised. Prior to starting a work procedure, workers will be able to watch a video on the safe operating procedures of the plant (as refresher safety training) by scanning the barcode or quick response code (Lingard *et al.*, 2015) on their smart phone or smart glasses. Similarly, any onsite safety training will be conducted using the same technology: by scanning the barcode on the plant or machinery.

Plant and machinery maintenance crews will receive automatic updates on the usage of the plant, and all manuals and documentation in the system will also be auto-updated. The appropriate personnel will be alerted to overloaded or malfunctioning plant based on the automated control system (RFID Journal, 2009, 2010).

5.3.2 Real-time safety management system. The smart construction site of the future will be proactive against accident risk. In particular, due to the dynamic and complex nature of construction activities and the increasing interaction between various objects on site, there will be automated controls for collision avoidance, as well as accident prevention through proactive risk identification and mitigation (Edirisinghe, Blismas, Lingard, and Wakefield, 2014). The digital skin sensors/objects will collect a large number of context parameters in real time, embedded real-time intelligent models will analyse (through big data and analytics) the gathered context parameters, forecast risk and adapt to potential hazardous situations (e.g. by providing early warnings, and notification of near-misses).

Automatic safety control. Automatic safety management on the future construction site is illustrated in Figure 7. Site safety and access management will be automated (RFID Journal, 2013b). Site environment conditions such as temperature, humidity, ultra

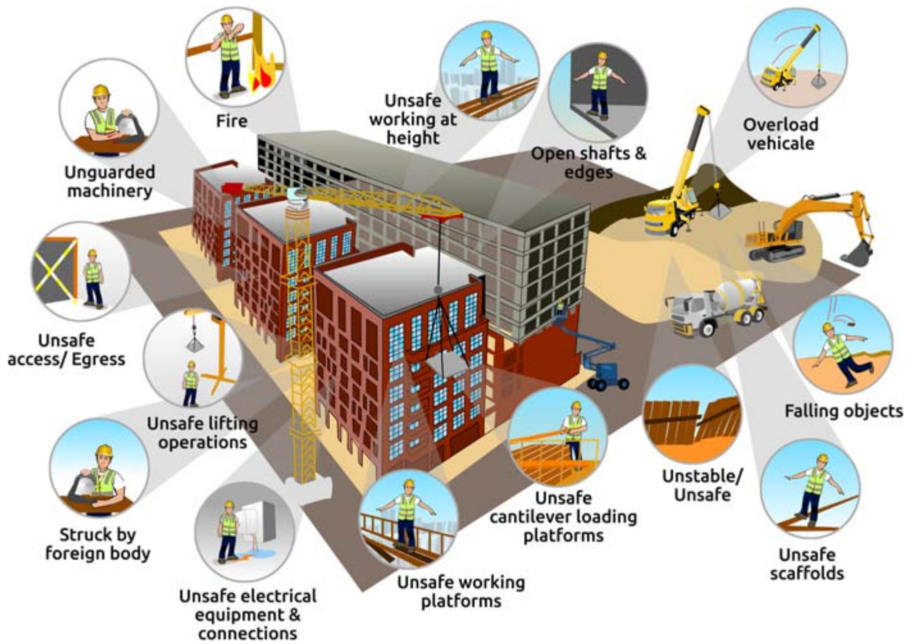

Figure 7.
Future construction site safety management

violet light and air pollution levels will be monitored and visualised on BIM (Riaz *et al.*, 2014). If the conditions are unacceptable or unsafe, management and workers will be warned (e.g. of fire, as shown in the figure). Work exclusion zones will be monitored in real time and access to unauthorised areas will be tracked (Edirisinghe, Blismas, Lingard, Dias and Wakefield, 2014) (e.g. unsafe lifting operation, unsafe access/egress, as shown in the figure).

Workers will be alerted to possible falling objects as a result of unsafe lifting operation, as shown in Figure 7) from overhead (Carbonari *et al.*, 2011). As discussed in the plant operation section, plant and equipment will carry tags so that overloaded vehicles, plant operating in close proximity to workers or multiple plants will be tracked, reducing risk of collision. Since almost every object on site will be part of the digital skin, unsafe working heights, open shafts and edges, unguarded machinery, unsafe scaffolds and unstable platforms will be tracked and risks to workers will be controlled.

Health and safety communication. Safety communication includes orientation training, short refresher training and the communication of rules, procedures, policies and legislative requirements for safe ways of performing day-to-day work procedures. Examples of such requirements include safe work method statements or job safety analyses for high-risk activities in Australia, or risk assessments for high-risk activities in Singapore. All these training materials will be part of the automated safety control system. All such health and safety policies, regulations and related documentation will be part of the automatic safety control system.

Video-based health and safety training has been identified as a more efficient way to communicate policies, procedures and rules to construction workers due to potential literacy and comprehension barriers (Lingard *et al.*, 2015). On the future construction site, safety training and tool-box meetings will be more interactive (to suit generational and adult learning needs) and also more visual; training will be conducted using real-time data visualisation (Teizer *et al.*, 2013) or by scanning a code to play a video (Lingard *et al.*, 2015).

6. Discussion

Reviewed studies symbolise the ambition for the emerging vision of the "construction site of the future". The findings from the review and analysis suggest that there are gaps due to: lack of technology feasibility validation, technology application on site and technology readiness; limitations in user acceptance tests and adoption of mature technologies for wider adoption; promoting and supporting the innovation in emerging technologies. These challenges are discussed below.

6.1 Challenges to achievement of digital skin

6.1.1 Technology limitations. Limitations of hardware/sensors and software/applications. As introduced in Section 3, the key technological elements of the future smart construction site are the hardware, communication technologies and software. Amongst these, the essential and integral parts of the smart construction site are the sensors and hardware. However, the low reliability, low computational power and limited battery life of sensors and devices present challenges. The sensitivity of sensors and the accuracy of sensor data significantly affect the reliable functioning of any system. For example, the smart bracelet used by Yi *et al.* (2016) for monitoring heart rate suffered a transient malfunction during site testing. Similarly, the accuracy of sensors (Chen *et al.*, 2013) and GPS due to their dependency on external systems has been reported by many researchers as a limiting factor (Meža *et al.*, 2014; Jiang *et al.*, 2015).

In addition, as Meža *et al.* (2014) reported, one of the limiting factors for using AR applications is the limited hardware capability of mobile devices. About a decade ago, Ahsan *et al.* (2007) reported that battery power was a technological limiting factor, among many others, to the use of ICT in construction. Wireless sensors are also battery powered and still, as of the time of writing, have practical limitations to do with onsite longevity. In addition, there are also limitations specific to particular pieces of software. For example, geo-referencing and visual occlusion are challenges for AR applications (Meža *et al.*, 2014).

Thorough technology validation. Innovation is the key to cutting-edge research. However, rigorous validation techniques should be followed if the technology is to be used to its full potential. The TRL model recommends that technology be validated at the stages including: pre-concepts and basic ideas though proof of concept; applied investigation through laboratory or simulated environment; and development and operations through operational environment testing.

Technology feasibility testing should include thorough laboratory testing or experimental system evaluations in simulated environments (controlled set-ups) prior to taking the technology into a real-world setting. For example, in the study by Yi *et al.* (2016), the transient onsite malfunction could have been discovered during prior laboratory testing.

The next phase of technology validation in a real-world site environment should cover aspects such as ruggedness (Ahsan *et al.*, 2007), seamless onsite integration, better understanding of the demands placed on the technology in practice and a wide range of practical issues, such as the directions and ranges of radio waves on real-world sites (Goodrum *et al.*, 2006). For example, Meža *et al.* (2014) discovered practical onsite challenges which are common in reality when the AR technology was trialled that would have been difficult to anticipate in a simulation. Onsite testing can prove the robustness of the proposed system.

There are other factors to consider in technology validation, such as generalisability and scalability, which are covered in stage 7 of the TRL model, full, scaled-up system demonstration (pre-product with all requirements) in an appropriate generalisation of real or operational environment, which is part of the development and operations phase. Generalisability is the degree to which the system can work on any construction site. Once site tests validate the technology on a single site, it is important to consider whether the technology's effectiveness depended on any site-specific characteristics. Technology should be fully generalisable and applicable on any site. Scalability refers to the ability of the system to grow. For example, the scalability of a sensor network system with a pair of nodes can be tested by increasing the number of nodes that it uses. This may introduce a range of other challenges, such as problems with communication protocols, timing for communication cycles, network reliability, packet loss and resilience, etc., which are important to address to create a robust system. For example, Riaz *et al.* (2014) conducted testing in a real environment, but included only two sensor nodes. Such systems should ideally be scaled up in testing to realise the adoption of technologies to their full potential.

6.1.2 Technology acceptance. The literature analysis found that very few studies have evaluated the technologies from the social and human perspective. Regardless of how reliable, valid, generalisable and scalable the technology is, its implementation will not make sense if the users will not accept and adopt it, which is the ultimate objective of developing the technology. Hence, it is vital to have users involved in the technology development process. It is recommended that system users be involved in the technology development process at two different stages. The first is prior to starting the development process in order to capture user needs, and the second is during implementation to validate that the system meets user expectations, also called user acceptance.

User requirement analysis. It is vital to understand what the technology users' expectations are before a product/system/technology is developed. In software engineering, for example, user requirement analysis is a major phase in the development cycle.

Similar user consultation prior to onsite implementation is critical in the construction industry if the technology is to have the desired impact. None of the research studies reviewed has gone through this process. One reason could be that researchers from an industry background assume that they already know the industry's expectations. Kang *et al.* (2013) propose information technology (IT) "best practice", under which practitioners contribute to technology development prior to implementation by considering the processes and effects of the systems on project performance directly. Half a decade ago, Erdogan *et al.* (2010) argued strongly that "user-centred IT" should be developed for the construction industry. In their view, many of the promises to meet the needs and enhance the experience of ICT systems in the industry remained (and remain) unfulfilled. The present paper argues that a major part of the problem is that industry practitioners do not become involved early enough in system development so that the researcher can capture their requirements thoroughly, as would occur in software engineering.

If the technology is cutting-edge, requiring an intermediate RtP step between prototyping and real-world testing, user requirement analysis can happen then; user needs should be captured before the technology is taken to the site. The ultimate goal of this exercise is for the technology to make an impact in the industry. As Erdogan *et al.* (2010) argue, this is needed to increase the ability of organisations to adapt and improve upon current processes by adopting new technology.

User acceptance testing. After the technology is implemented and trialled in the industry, it is important to test whether the system meets the objectives and expectations of users. People transformation, managing change and fostering innovation, especially in the construction industry, which lags in technology adoption, can be very challenging. The social aspects of technology adoption in the construction industry have been studied by some researchers (Xu *et al.*, 2014; Levis *et al.*, 2005; Cao *et al.*, 2015). Some studies reviewed attempts to validate technology adoption by the users (Lee *et al.*, 2012; Jaselskis and Misalami, 2003). Jiang *et al.* (2015) note that full automation of the proposed technology is not possible due to unpredicted circumstances on site, where a resident supervisor's knowledge is critical. In another study on BIM, Xu *et al.* (2014) argue that improvement in the mode of thinking of adopters as well as potential adopters is the most important driver for wider adoption of BIM in the construction industry. In a similar study on BIM and AR, Wang *et al.* (2014) suggested that contractors should be actively encouraged to embrace AR technologies' intended uses and capabilities or they could find themselves entrenched in their comfort zones long term. In addition, Erdogan *et al.* (2010) argue that the better use of ICT will, in turn, require better education. Lifelong education, as well as self-directed learning, will be key in this regard. Technology up-skilling is always a challenge, but this is an emerging need, particularly among sub-contractors. Up-skilling will, however, be of least concern for the technology-savvy workface in the coming digital era.

6.1.3 Technology diffusion. Once the technology is validated and ready as an industrial product, the next step is its adoption by the industry. The analysis of the distribution of research areas identified gaps in research on emerging areas (safety, BIM, AR), as well as a lack of adoption of mature technologies, such as RFIDs and other tracking technologies. Innovation diffusion theories explain the technological individual and organisational and external dynamics of the factors affecting technology adoption.

The innovation diffusion theory (Rogers, 1995) measures the individual's perceptions on innovation characteristics such as relative advantage, compatibility, complexity, observability and trialability, and also considers the organisational-level characteristics. Compatibility refers to the ability of the innovation to coexist with the existing values, past experiences and/or applications, which is also referred to as "interoperability". Complexity is the degree of difficulty involved in understanding and using the innovation.

Observability is the degree to which the results of an innovation are visible to others. Trialability is the degree to which the innovation can be experimented with and tested prior to real use. Site testing of the technology can make a significant impact to the trialability factor. Relative advantage refers to the level of benefit to an organisation. Tornatzky *et al.* (1990) argue that technology availability is also a critical factor. Technology availability refers to the ability of the technology to function properly and to be available to meet user requirements reliably. Technology availability verifies the early involvement of the practitioner during user requirement capture stage prior to the technology development, which was discussed above. Tornatzky *et al.* (1990) also argue that organisational technology readiness (e.g. IT infrastructure and human resources) is also influential for successful technology adoption flagging the needs for up-skilling the workforce and training. One of the organisational leader characteristics is the leaders' attitudes to change (Rogers, 1995) and the way in which they, accordingly, set organisational priorities.

There are number of other characteristics outside the technology and organisational factors that can influence the innovation adoption, called environment factors (Tornatzky *et al.*, 1990) in which the organisations conduct their business and include the industry, dealings with the government, competitors and other stakeholders. In particular, in the construction industry government and industry effects are strong influential factors. Government-driven innovation is referred to as top-down approach while the industry-driven innovation is referred to as bottom-up approach. Pressure from competitors and peers, in a highly competitive industry, impacts an organisation to adopt new technology. Other stakeholder groups in the workflow that have already adopted the technology in the organisation (e.g. other departments in the workflow, vendors and contractors in the construction industry) also influence the adoption.

The role of government and industry in promoting wider adoption. Moore and Benbasat (1991) emphasise the significance of adoption being compulsory or voluntary and includes another dimension called "voluntariness of use" to the Rogers (1995) model. According to Moore and Benbasat (1991), the organisation's freedom of choice to reject or adopt the technology depends heavily on the degree of compulsion involved. If there is a corporate policy regarding technology innovation either mandating or discouraging a particular innovation, such a policy takes the freedom of choice of rejection or adoption out of individuals' hands. Supported by this theory, researchers have argued that innovation adoption in AEC industry (e.g. BIM) can be fostered by national and state-level policies (Manley and Mcfallan, 2006; Edirisinghe and London, 2015). In contrast, Loosemore's (2015) research argues for industry-led rather than regulation-led innovation. Rewards (Gu and London, 2015) and subsidies (Singapore Government, 2015) are also considered as influential factors.

While the debate on the impact of policy on innovation is ongoing, there are examples of strong policies that mandated the use of technology in the construction industry (BIM policy in the UK and Singapore). A study on organisational motivation to adopt cloud computing by Marston *et al.* (2011) reported that compliance with regulations is an influential factor that can make firms reluctant to adopt technology. The lack of standards was reported to be a serious obstruction to decisions to adopt new technology for which the industry and academia both have a great deal of responsibility.

6.1.4 Standardisation of technologies. Standardisation of technologies is a burning need in the construction industry. A decade ago, Goodrum *et al.* (2006) flagged the need for standardisation of RFIDs in the construction industry. Five years later Erdogan *et al.* (2010) highlighted the need for standardisation and adoption and understanding of common regulations and policies. In order for IT to play its full part in the construction industry, it is thought by many that defined and open standards should be agreed upon and used by all stakeholders.

Recently it has even been argued that the lack of standards may be limiting the widespread adoption of technology in construction (Kelm *et al.*, 2013). Future standardisation efforts might include specifying unique identifiers for objects, such as construction ID cards and PPE items (Kelm *et al.*, 2013). Wang *et al.* (2014) also argue that there is a need for standardisation of tools and data sets, and they argue that there should be a unified approach. Part of the standardisation process will be to build a system to allow benchmarking and control.

A new, innovative factory for construction was set up with state-of-the-art production and prototyping equipment in which companies were able to test new products, processes, systems and solutions, from early stage ideas to commercial launches (CIOB, 2017e). Such facilities and test-beds, if widely accessible, can foster rapid standardisation across the sector.

6.1.5 Economic challenges. The economic impact of these technologies is also to be evaluated by gathering feedback on user and industry acceptance. While the technologies are still maturing there are also economic challenges. For example, researchers consider the cost of equipment to be a barrier to technology adoption in the industry (Wu *et al.*, 2010; Goodrum *et al.*, 2006). Khoury and Kamat (2009) also argued that implementation cost is a major obstacle to taking technologies beyond laboratory experiments. More recently, even though promising benefits and enhanced human capabilities were demonstrated (CIOB, 2017a; Eskobionics, 2017), exoskeletons remain in their infancy due to their lack of affordability for some contractors.

The challenges discussed above and the influential factors along the technology development life cycle are visualised in Figure 8.

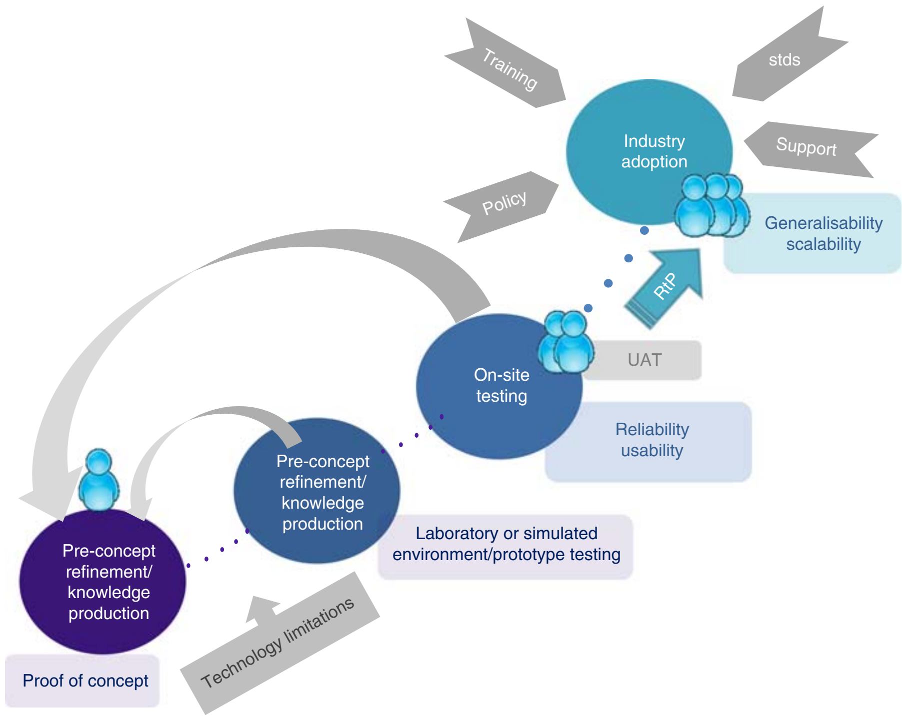

Figure 8.
Challenges and the innovation lifecycle

6.2 Are we there yet?

The benefits of digital skin research include automation, improved productivity, enhanced human capabilities, enhanced communication and vision and enhanced strength. The strategic need for research and innovation of smart technologies in the building and construction industry emerged in the recent past. For example, in 2015 the International Council for Building formed a task group on wearable sensor technology (TG 92) to encourage research and innovation in wearable technologies in construction.

There has already been an enormous amount of research done which can contribute to the context-aware digital skin of the future pervasive construction site. It can be envisage having Sensor Andrew (Rowe *et al.*, 2011) on construction sites in future which has wide range of sensor, actuator and low-power applications. However, there are research gaps to be filled on the subjects of standardisation, the development of guides and the benchmarking of new technologies as well as the technology development process. Given the poor performance of the construction industry in innovation, it may be that new technologies are perceived by the industry as brutal. Thus, challenges exist for these innovations/technologies when contributing to the paradigm shift in an industry which is far from being a trailblazer. As such, proponents of innovations offering solutions to existing problems, or improvements to current practice, should take measures to minimise brutalism. Researchers should also be sure to follow a coherent process of development and implementation. Technology limitations are addressed by technology developers on a daily basis. According to Moore's law (Schaller, 1997), with the advancement of the electronics industry, making faster, smaller and more affordable transistors increases processing power, performance and energy efficiency, and decreases cost, making pervasiveness affordable. Hence, this paper argues that the context-aware digital skin of the future pervasive construction site will come to realisation in the near future.

The technologies that enable the context-aware digital skin of the future smart construction site should not stand in isolation from one another at the micro level. As Harty *et al.* (2007) argue, it is paramount that the connections between global, local, construction-specific and more general or macro-level factors be explored once the technologies are integrated in practice. In order to understand the challenges, opportunities and connections of the bigger picture of the future construction site, of which digital skin is an element, it is vital, with the engagement of industry, that these connections and future scenarios be mapped over the next decade or two (Goodier *et al.*, 2009).

7. Conclusions

While a clear definition of the new vision of the construction site known as the "construction site of the future" has been lacking, various research projects and promising technologies have emerged to contribute to it in recent years. This paper contributes to the field by providing a coherent, high-level view and a definition of the use of technology on the future construction site referred to as the context-aware digital skin. Key aspects of the digital skin, such as hardware, communication technologies and middleware/software, have been discussed. The systematic classification and critical review of the existing research has revealed that there are open research challenges and gaps to be filled in the body of knowledge. These include the limitations of hardware and software, the lack of standardisation efforts, the absence of a coherent process in technology design, development and implementation and the lack of effort on studying technology acceptance and human transformation in technology adoption. As the challenges of technological limitations are gradually being addressed by other disciplines, this paper recommends that researchers and regulatory bodies in the construction domain make an effort to bring these promising technologies to the construction industry through a systematic process of standardisation, validation and acceptance of technology.

The paper also imagines the future construction site, using scenarios to consider the future construction worker, smart plant operation, smart supply chain and smart real-time safety management systems. The holistic and cohesive view on the gaps between the research and practice provides the first comprehensive source of checklist for the researchers in the field. It also provides useful insights for stakeholders for achieving the future smart construction site. It is anticipated that this paper will aid in achieving the vision of the future smart construction site.

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