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Digital construction: From point solutions to IoT ecosystem

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ABSTRACT

This paper takes a longitudinal view of literature to explain the current period as disruptive technology drives an evolutionary adaptation of the construction industry in a historical socio-technological process. The authors argue the way Internet of Things (IoT) solutions are conceived as singularly focused "point solutions" undermine future opportunities. An evolutionary view is overlooked because extant literature describes technology in a particular epoch. An ecosystem perspective needs to influence IT strategy as an emerging "digital layer" transcends a smart city and continues to function long after a traditional construction project completes. We describe innovation as a succession of transformational waves in an evolutionary process that is currently manifesting as "Industry 4.0" and changing expectations for the construction industry. The paper concludes by listing emerging trends and warns existing UK construction companies must understand the transformational process they are in and learn how to adapt with a stronger drive for R&D.

1. Introduction

The aim of this paper is to share insights from a literature review that explains the construction industry is in a transformational stage of a larger evolutionary process. In the UK this is known as "Industry 4.0", but a similar version in the USA is known as the "Industrial Internet" and we can also see a version in China emerging [1]. They all seek to bring IT innovation into a world of Process Control Domains and Operational Technology.

Its objectives are:

- Enable a wider view of transformational socio-technological processes in society.
- Establish a necessary link between the evolution of the UK construction industry and the evolution of its context, such as a smart city.
- Distinguish the evolution of "Information Technology" (IT) from the evolution of "Operational Technology" (OT) and the challenges in their convergence.
- Show examples of "IP Addressable" protocols and "non-IP Addressable" protocols to highlight key challenges of IT merging with OT (i.e. Process Control Domains).
- Outline security threat sources and implication for sharable data.
- Explain the implications for an IoT enabled UK construction industry.
- Demonstrate examples of an evolutionary process for technology being used in the construction industry.
- Build on the realisation we are in an adapting evolutionary process and outline future research directions.
- Form conclusions that help construction companies to reflect on the way they currently view digital transformation.

2. The case for change

The UK Government is grappling with significant challenges that impact the UK construction industry revenue at the same technology is having a disruptive effect:

1. An agenda of "Austerity" causing a "squeeze" on public sector funds and given the UK Government accounts for around 40% of total revenue for this industry [2], this must be reducing the number of major projects as funding is harder to source.
2. The lack of affordable housing is driving social pressures to increase residential house building (e.g. Mortimer [3]). Indeed, house building is currently the main growth area in UK construction output [4].

At the same the UK construction industry also has its own challenges:

3. Twenty-two percent of construction employees are over the age of 50 and 15% are over 60 year old [5]. We see this pattern in other

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industries such as the Oil & Gas industry where the "Baby Boomers" of the 1960s reach the end of their working careers and the "Big Crew change" [6] becomes an issue because succession planning has not been managed well. This represents a potentially significant loss of expertise and experience for those companies that have not planned for it. We see a risk hollowing out presenting itself in the construction industry but would be less risky for companies that have embraced digital transformation as new ways of working become possible, such using collaboration tools and "distributed leadership" [7].
4. With Brexit in mind, the Governor of the Bank of England, Mark Carney, warned that uncertainty is holding back investment [8] on a number of fronts which either directly impacts construction through cancelled projects or indirectly through stalled business strategies that could eventually become construction projects.
5. Perhaps even more worrying are claims that Brexit could mean a loss of 8% of its workforce, meaning some 175,000 vacancies [9] might need to be filled, but from where if EU migration is curbed?

From this view of the situation in 2017 faced by the UK construction industry three significant contradictions stand out clearly:

1. The Government needs to build more but for less cost
2. The construction industry needs to deliver more with less skills available
3. The private sector needs to invest in projects (i.e. Increase CAPEX) whilst uncertainty makes the evaluation of Return On Investment difficult to quantify.

These three contradictions are calling for growth and shrinkage at the same time and so represent very difficult challenges to overcome. Given a labour intensive construction industry of today relies heavily on cash flow portfolio, this "squeeze" is most likely to heighten a desire for short term success criteria, the very opposite of what the long term needs for a slow and managed adaptation to new ways of working and a more capital intensive construction industry.

The Farmer Report [10] outlines a case for digital disruption in the UK construction industry. It sees the following "critical symptoms of failure and poor performance" as:

- Low productivity
- Low predictability
- Structural fragmentation
- Leadership fragmentation
- Low margins
- Adversarial pricing models & financial fragility
- A dysfunctional training funding & delivery model
- Workforce size & demographics
- Lack of collaboration & improvement culture
- Lack of R&D & investment in innovation
- Poor industry image

This is set against an industry which is not applying for billions of pounds of R&D Tax Credits, set up by the UK Government to stimulate innovation [11]. The authors believe that the "case for change" has not been accepted by incumbent leaders in the UK construction industry.

This discussion paper draws insight from a literature review and the industrial experience of the authors involved in many different technology led transformation projects in a number of industries such as Defence, Oil & Gas, Manufacturing, FMCG, and Retail. It explores the potential impact of the Internet of Things (IoT) on the construction industry and its customers. It warns against the temptation to get locked into point solutions that diminish the ability to extract data from across the construction industry. One only has to think about Alphabet's Smart Neighbourhood project in Quayside, Toronto, Canada, [12] and an overarching "digital layer" across a city, to see new possibilities for the construction industry to extend its role in the built environment with data driven services.

It is important to recognise a recurrent theme which is not explicitly called out in the literature that comprise a series of technology epochs. An underlying pattern reflects an evolutionary process between technology and society, each shaping the needs and expectations for the other. By seeing our current position in the context of an evolutionary process we can begin to glimpse emerging trends [13].

The search for new opportunities begins by recognising technology as a key disrupter of societies over thousands of years so that what is happening today is viewed as a "natural" progression humanity has experienced many times before.

With billions of low cost sensors becoming available, data will flow from "information blind spots" to augment and improve decision making. This focus on sensor networks, especially wireless sensor networks, is what is typically referred to as "The Internet of Things". A "thing" being an object that has a sensor on it or in it, within a transcending heterogeneous computing "ecosystem".

We argue that a key step for construction companies is to recognise a "planned IoT ecosystem" has a long term advantage over trying to combine many "point solutions". By ecosystem we mean an integrated "layer" of hardware, software, connectivity, and information flows linked to key decision making activities. This "layer" is much wider than the construction industry itself and includes all industries that play some kind of role in a continually adapting built environment such as a smart city. This definition is necessary to show a glimpse of future states a construction industry of today will need to adapt towards, or be left behind by new entrants.

By "point solution" we mean an IT offering that has a singular focus on one problem, or one use-case, in a stove pipe type of solution. An example could be a typical Project Planning application used today that is disconnected from what is happening in the supply chain, on site, meteorological risks etc. This "singular" focus usually leads to silo-solutions that make real-time data inaccessible to other solutions.

By understanding we are in a period that has been seen in history many times, we argue that failure to recognise the need to transform will present significant risk to the long term viability of "change resistant" construction companies. In the next section we explain this repeating pattern throughout history.

2.1. We are living in an industrial revolution

The history of humanity can be explained in terms of significant technological impacts. The stone age, bronze age, iron age, steam age, computer age and so on are examples of technological impacts that changed the way society works. Kondratieff explained a cyclic progression of technological disruptions in terms of waves of innovation [14]. What is happening today is itself one wave that is part of an underpinning natural socio-technological evolution.

Probably the most famous wave is the first "Industrial Revolution" but there have been others such as the Deep Plough enabling Northern European countries to grow more crops than they consumed and shifting economic power away from the Mediterranean countries to Northern Europe around 1100 CE [15]. As these technological waves unfold they ripple through many aspects of society, and disrupt established power structures leading to new institutional governance frameworks designed by incoming agenda (e.g. The emergence of labour markets, wages and rents as feudalism and serfdom gave way to the economic prowess of emerging of towns and cities such as Norwich and Newcastle in the 1300s).

Some in Europe are calling this current wave of IT innovation the Fourth Industrial Revolution, or "Industry 4.0", and in North America, the "Industrial Internet". We see these as labels attached to a deeper technological evolution of what we typically call "The Internet". This paper argues a combination of digital innovations collectively called the Internet of Things (IoT) will bring new emergent needs and capabilities that cause the construction industry to adapt as new institutional requirements shape demand. At its root is the availability of information from sensors to improve decision quality as has never been previously possible at such a scale.

The pace of an industrial transformation is hard to predict and affects whether established companies can take their time and adapt slowly or need to adapt quickly or be displaced. Indeed, the move from hand craft to mechanical processes in the First Industrial Revolution took about seventy years from 1760 to about 1830 [16]. The Second Industrial Revolution, driven amongst other things by the telephone and the internal combustion engine, lasted about 96 years from 1870, interrupted by the First and Second World War, then continued up to about 1970 [17]. The Third Industrial Revolution, predominantly a digital revolution, is viewed by some as starting in about 1980 as Personal Computers became affordable, and is still unfolding some 38 years later [18]. A parallel story of the evolution of algorithms and IoT uses a notion of information value to highlight significant academic papers and makes an argument that RFID was the seminal idea for IoT [19]. The Fourth Industrial Revolution is where compute power becomes more embedded within society and even inside human beings [20]; Tesla are currently working on implants that would be inserted into a human brain to overcome problems such as enabling blind people to see with a Brain Computer Interface (BCI).

Schumpeter [21] explained the challenges when new ideas smash into established structures as “Creative Destruction”. Just as the day Samuel Morse invented the telegraph was a bad day for the horse back messenger, significant technological disruptions can be destructive for older more established workflows that do not adapt. Christensen [22] borrowed and extended Schumpeter's core ideas to explain how the Western World would adapt through a period of “technological disruption”. In a similar theme, Leonard-Barton [23], explained why many organisations fail to adapt during such periods of structural change due to early successes becoming rigidified in their operations and how they see the world (e.g. Blockbuster Video were unable to adapt to the digital challenge Netflix posed, partly because they did not believe it would be successful until it was too late). Core rigidities are a particular risk for the UK construction industry today as demonstrated by the poor uptake of R&D Tax Credits provided by the UK Government to stimulate innovation.

Technologically originated change and its consequential effects is a complex blend of many socio and technological variables that are confounding until they stabilise in a new kind of equilibrium, a homeostasis. Heilbroner [24], a Nobel Prize winning economist questioned whether we actually control technological progress or if technological progress controls us. This is a view of technological determinism that forces us to question what technology is itself [25]. To shape societies over millennia suggests “technology” is far more than a physical device (e.g. a stone-age axe made from wood and flint or a modern mobile phone). It seems we confuse an instance of technology with waves of technological progress and so lose sight of an underlying evolutionary process. For example, when Henry Ford started to mass produce the Model T the need for roads, road signs, car parks, traffic police and so on, rippled outwards as humans and technical systems started doing things in new ways, but with some unanticipated side effects. The Model T was an instance of technology but the rippling waves of progress are a transcending phenomenon. We argue, technology is a gestalt relationship between the technological-instance and transcendent effects [25]. This outward ripple of ‘invention stimulating invention’ takes on a momentum of its own. When undesirable side effects become apparent, such as car pollution becoming a problem, it is difficult to stop the innovation wave.

At the heart of this paper is a realisation that we are living in a period where adaption, necessitated by disruptive technology, is itself an evolution of the Internet and will cause the next evolution of society and its institutions. We will limit our consideration to construction companies and how reducing uncertainty through data acquisition and data conversion to information offers a source of advantage to companies willing and able to ride these new waves of change [26].

3. IoT and digital transformation

How can UK construction companies learn from digital disrupters? If we examine the rise of companies such as Netflix, Uber, Airbnb etc., we can see their advantage. Netflix made it easier for people to download a movie rather than travel to a video store such as Blockbusters. Uber reworked information flows and payment mechanisms to make ordering a taxi that arrived when and where a customer needed it easier than standing in line at the taxi rank or trying to flag a cab on the street. Airbnb opened ways for people to be a pop-up hotel and make low cost accommodation much easier than was the case previously; Airbnb is now the largest hotel chain in the world but does not own a single hotel. All end up with a better value proposition for customers willing and able to pay for something because of new information flows.

The key insight is to recognise that digital disrupters rework information flows to reduce customer uncertainties and so improve the customer experience of a service being offered. By doing this they can move economic power in an established value chain such has been the case with Netflix, Uber, Airbnb etc. For construction, this can be about sensors attached to “things” such as sensors in the building fabric to monitor interstitial condensation and consequential corrosion.

Gartner [27], a key commentator in the IT Industry, say there will be 8.4 billion connected “things” in 2017, up 31% on 2016. We have already seen companies such as British Gas offering home IoT solutions such as “Hive” and Google offering “Nest”. Home IoT is entering many houses, but again, they are usually single point solutions that rarely integrate to give any notion of a transcending intelligence. If data was shared amongst different home IoT solutions then it would be closer to an ecosystem view of IoT. For example, the opening and closing of windows influenced by temperature and humidity as well as anticipating the temperature in say the next 5 min and automatically adjusting settings for the heating system, all with Machine to Machine (M2M) interactions. The reason this is not easy is because data gets trapped inside an application's solution boundary. Service Oriented Architecture (SOA) offers a way to mitigate this but assumes all the different solution providers are working to the same SOA ideals and standards. Wireless Sensor Networks added a need for a new layer in SOA models [28] as evolutionary waves moved from narrow requirements to much broader ones. This is in part assisted by scenario based approaches to functional and non-functional requirements [29]. Even approaches like SOA are themselves evolving.

Most people have experienced the Internet but a “thing” is often not understood. It is simply any object that has an Internet Protocol (IP) address and sends data about its state and its immediate environment (e.g. temperature sensors inside a specific car's engine). A thing can also receive data linked to actions (e.g. trigger an actuator to open a valve that allows more coolant to flow around the engine). Examples of “things” could be a (i) concrete mixer at the base of a skyscraper, (ii) a “smart” pipe measuring concrete flow rates as gas is introduced to temporarily reduce concrete density without compromising integrity, (iii) a human operative having their health assessed whilst working in a dangerous location such as pouring concrete on the top floor of a skyscraper during winter. Collectively the individual tasks become an end-to-end process, a workflow that can be managed better through real-time data.

From not knowing if the concrete trucks have really left the batching plant to being able to track them in real-time helps site staff be better prepared for their arrival. Using such an approach on other stages of a workflow means productivity improvements are more feasible. It also offers an opportunity to develop different relationships with customers so the work is done “with” them rather than “to” them. The use of “distributed apps” in a peer to peer architecture, rather than say a client-server architecture, that take advantage of Blockchain are available to us now and used in some supply chain solutions. It is the distribution of multiple copies of a single block of validated transactions that ensures a "single version of the truth" persists in many places. Trustable data is the primary advantage of Blockchain technology and can be used in new applications that seek to improve situations were low levels of trust exist. For example, in supply chains [30] this means we can integrate electronic "proof of delivery" and track supplier payments throughout the supply network to make sure everyone is paying on time. Construction companies that currently exploit commercial power today should start to think about their reputations as "transparency" becomes the norm. The internet will increasingly promote trust. Those companies that treat other companies fairly would be expected to enjoy opportunities that will be denied to less trustable rivals [31].

Blockchain has many potential use-cases in construction enabling unique part traceability to smart contracts and documents by combining RFID technology.

The strategic advantage of an IoT strategy is to see it as one facet of a bigger more encompassing Digital Transformation [32]. By integrating different data streams across a number of silo, a clutch of new insights becomes possible.

As IoT enabled solutions emerge and integrate with other IT innovations such as Big Data and Artificial Intelligence (AI), we will see new skills emerge as some traditional jobs become digitally displaced (e.g. the work of cost estimators could be automated) and new jobs arise (e.g. Construction Data Science). We should also expect to see new tasks undertaken such as monitoring the state and health of embedded sensors on a construction site and beyond, as a service Facility Management buys from a digitally savvy construction company.

McKinsey [33] claim the effects of automation will be very significant globally so this is wider than the construction industry:

> "On a global scale, we calculate that the adaptation of currently demonstrated automation technologies could affect 50 percent of the world economy, or 1.2 billion employees and USD $14.6 trillion in wages. Just four countries—China, India, Japan, and the United States—account for just over half of these totals."

The digital revolution is here and it is happening.

3.1. IT evolved independently from Operational Technology and Control Systems

To better navigate the transformational waves of today, it is important to understand how and why the current landscape has evolved as it has. In this section we will focus on the evolution of IT in order to see how the current challenge is about converging with Operational Technology (OT) in the next section of this paper.

The goal of companies is to reduce the cost of needed functionality which does not differentiate products and services (i.e. overheads). Porter's "Value Chain" [34], insights that have stood the test of time, show two key foci:

1. Primary value adding activities (e.g. inbound logistics, operations, outbound logistics, sales and marketing)
2. Secondary supporting activities (firm infrastructure, human resource management, corporate IT, and procurement).

The commercial evolution of Information Technology (IT) based around the desktop PC to Enterprise Systems (ES) began with firms needing supporting activities that customers did not want to pay for. This saw the emergence of "Systems of Records" solutions such as ERP [35] (e.g. SAP or JD Edwards), MES (e.g. Oracle or IQMS), MRP (e.g. Maximo) and many other types. This evolution brought disparate data stores together and a move away from MS Excel Spreadsheets which opened the possibility for Big Data. Firms were looking for ways to perform supporting processes, faster, better, cheaper and the IT industry saw opportunity. This desire to reduce the cost of indirect costs also led to the idea of Outsourcing as a way to reduce costs that offered no competitive advantage. The world of Outsourcing, which had to justify value for money in competitive markets, triggered the emergence of Enterprise Systems (ES). ES is an evolution of the old IT Department responding to IT problems and attempts to link IT investment to value creation.

The IT industry has, by and large, focused on secondary supporting activities with large payroll systems, enterprise resource planning systems and so on, because they could become scaled solutions generating large revenue as pricing models were often based on the number of end users (i.e. seats). As web applications opened ways for end-users to engage with many of these enterprise solutions we also saw the role of the Internet evolve, especially with the Mobile Internet.

It is important to recognise IoT is itself an evolution of the Internet. Before 2010 the Internet was architected around a client (i.e. a GUI or an App on an end user device) that sent data in packets via transport protocols to a server, typically in a data centre. This "client-server" architecture (which later evolved into "client-server-service" architecture) had requests originating on an end-user device (e.g. a PC or Mobile Device, that is a 'client') used HTTP protocols such as "get" and "post" (and other) commands to send a request to a server. The job of the server was to process the incoming data, and enable an IT service to calculate some answers with the received data and send it back to the client in a rendered html page.

The most common internet transport protocol is TCP/IP (Transition Control Protocol and Internet Protocol). Transition Control Protocol handles the way messages are packaged and sent though the Transport Layer of the Open Systems Interconnection (OSI) seven layer model. Internet Protocol (IP) is an addressing process that is used during routing from A to B. TCP gets receipts from routers and if one fails to arrive it tries to send the packet again. TCP reliability comes at a price because it causes problems for real-time requirements due to packet resends. An alternative approach is User Data Protocol (UDP) which is faster but it does not do error checking so is prone to lost packets (This may not matter with some types of streaming data such as video).

People soon realised a sensor could be set up to send data over either TCP/IP or UDP/IP and so new possibilities arose, especially as Web 2.0 enabled dynamic webpages to be built rather than the old approach which served up static webpages.

Now data from user requests on end-user devices could be mashed with data from sensors sending more information-rich pages back to the client. The key issue here though is the quality of connection from the end-user device to the server (i.e. various communication technologies based on radio waves, such as Ultra Wideband, Narrowband, LoRA or others).

Two other innovations in parallel also changed the IT landscape, Cloud and Virtualisation. Virtualisation is essentially software pretending to be hardware. This evolved to enable IT services to run through software defined versions of networks, storage and so on and made guaranteed service more reliable because of a reduced dependency on the physical infrastructure. If a service is running in a virtual server which itself sits inside two or three physical servers, there is an insurance policy of redundancy. When one of the physical servers breaks the virtualised service continues across other physical servers without the end-user noticing anything went wrong.

We also saw R&D in home compute advance. Games such as PlayStation wanted players to network in real-time which led to innovation in Graphical Process Units (GPUs) and advances in the speed algorithms could run at. It was not long before ideas in Games and home automation led to adaptation in Industrial IoT context (e.g. Location Based Services to track assets in a factory).

An organisation working across many time zones started to think of their IT Estate (e.g. a static physical estate) as a dynamic and virtualised IT ecosystem. Some technologies such as ERP systems could be leap frogged by a more federated Big Data approach and we also saw the emergence of edge analytics start to question why we send 'all' data from the edge to the data centre at the core of a private network. The need for integrated project delivery rests on this ability to make data in one application available to another. The reality is that challenges such as common data exchange standards, inconsistent metadata, Application Program Interfaces (API) not working as well as they could, and asynchronous performance issues are already being grappled with through National BIM Standards (NBIMS), Construction and Operations Building Information Exchange (COBie) and National CAD Standard (NCS) to name a few. The authors experienced a similar situation in the Digital Oilfield and believe the root problem is a missing data strategy that links to a 'bigger picture' such as a smart city. The key point here was an ambition for different company ecosystems to combine into an integrated Digital Oilfield ecosystem. With things like Agile Project Management we saw new thinking emerge which wanted to erode silo thinking and access more integration and orchestration. This also manifested in the act of IT development as a concept called DevOps.

3.2. The emergence of DevOps

An Intellectual property problem was recognised by non-IT customers. The IT firms wanted to develop solutions they can sell to many companies. This represented a potential loss of competitive advantage to the prime customer as their rivals could buy an automated solution and acquire capability it previously lacked (i.e. nullify the prime customer's competitive advantage).

A different strategy emerged that seeks to make it easier for customers to develop their own solutions by pushing IT complexity down into the IT stack. This was known as 'DevOps' where the developer no longer needs to worry about the underlying IT infrastructure as they work in software containers (e.g. Docker) which 'plugs in' to a platform. Virtualisation and a platform means the developer can focus more on meeting the business challenges and creating business value than getting caught up in infrastructure complexity.

DevOps also challenged an 'over the wall' approach to IT project management where one team passes part of the developing solution to the next team along with its bugs, defects, and inadequate or missing documentation. This 'over the wall' approach places a need for steep learning curves to be repeated along the life cycle and has been problematic for many years. DevOps combines development and operations so the same team has through-life responsibility for the application's performance and quality. However, this approach could be used as a way to deliver a 'point solution' as a service and so can itself become trapped inside a silo mentality and lose ecosystem wide benefits such making data available to other DevOps teams building new innovative solutions.

DevOps is often achieved by breaking applications into composable components (e.g. One team will be responsible for an AI application that predicts the probability of an accident in the next 10 min and another team will be responsible for a dash board the predicted accident will be presented on, along with outputs from other apps). Key to this is the idea of 'containers' and 'microservices'. A microservice is a program targeted at solving 'one problem'. It is deployed into a 'container' (e.g. Docker) which is a self-contained unit with its own data. The beauty of a container is it makes putting one on to a cloud platform very easy. It also makes it easy to pull it off and migrate it to another vendor's cloud if needed. We can see how the idea of SOA itself is evolving.

A recent innovation is "Serverless Architecture" [36] which again removes complexity from application developers. Of course, servers are still needed but the developer does not need to worry so much about them as cloud services handle that complexity. Yet another idea that evolves out of a subsequent stage of SOA.

The trend in IT innovation is to free developers from IT complexities so they can focus more on customer centric issues that create business value. From the above discussion with evolutions of virtualisation into 'software defined everything' we saw the emergence of the Industrial Internet of Things (IIoT) and from home compute we saw IoT emerge. It was not long before the agenda was about 'converging' them in the workplace.

3.3. Process Control Systems and Operational Technology (OT)

Whilst the evolution of IT is clear to see, Operational Technology did not advanced in the same way or pace. It is not unheard of to find manufacturers running control systems using Windows 98 because it has dcom (Distributed Component Object Model) which enables communication between different devices in an operational context such as a factory floor. There are other 'differences' between IT and OT we will discuss in this section. Understanding these will help to see some of the technical challenges and security concerns as IT and OT converge.

Ironically, IT innovation in the primary activities of Porter's Value chain, particularly around operations, did not advance at the same pace. In the main, Operational Technology (OT) was separated from the TCP/IP centric Information Technology (IT). This is a world of Process Control systems comprising equipment (e.g. compressors), process flows (e.g. production lines), sensors (e.g. vibration sensors) and actuators (e.g. mechanisms that open and close valves).

Where IT advanced with different network technologies based around unique IP addresses, OT did not in a consistent way. Many things (e.g. a pressure sensor) in OT often operated with no unique network address. Equipment in OT typically run inside what is called a Supervisory Control and Data Acquisition (SCADA) system. In some industries an OT estate is also called a Process Control Domain (PCD). The point being made is OT did not evolve in the same way IT did. This is important to understand, especially if offsite production uses Process Control Systems (e.g. Uses OSI Soft's "PI Historian" or GE's "Proficy") and there is a need for better real-time integration with BIM applications.

The benefit of segregated OT was it offered a sense of security as people on the Internet could not access it. The problem was other IT innovations such as virtualisation, Cloud and Big Data were seen as offering valuable outcomes if only they could be deployed in the OT world [37]. Such benefits required IP addresses and the combination of data from different sources in the corporate IT estate (e.g. HR records). The calls to converge OT and IT began (e.g. ATOS, [38]). IoT is now driving innovation that links OT and IT with emerging standards called "Industry 4.0" in Europe and the "Industrial Internet" in North America.

This industrial focus for IoT comes from compute power being embedded inside 'things', objects with sensors and compute power in or on them. An IoT solution with embedded compute in 'things' is part of an end to end solution that is often modelled as a workflow. It involves a network of computing resources such as processors (CPU and GPU), volatile and persistent memory/storage, networking software, applications, analytics algorithms and so on. At one end of a spectrum are dumb sensors embedded into or on to 'things' broadcasting data (i.e. embedded sensors). Next there are smart sensors which have simple algorithms running such as only broadcasting values in a certain range to maximise battery life (i.e. smart sensors). Finally we have an embedded and autonomous computer in say an engine that uses machine to machine communication to regulate flow rates without any human involvement (i.e. embedded compute).

Sending and receiving data can be automated in IoT solutions. Imagine we wanted to know the temperature on site in some 'cold' remote location, every 5 min whilst pouring concrete. The above approach with manual data entry would be labour intensive, error prone and tedious. So, innovations have made measuring the physical world and submitting measurement data much easier and automated. It is often possible to do some analytics on the sensor or nearby but the most common approach is to send data to a cloud or to dedicated servers in data centre.

We still need experienced and knowledgeable staff and have seen other industries try to tackle a similar problem where a combination of domain knowledge and IT knowledge was needed to drive the Digital Oil Field (DOF) agenda. A similar need will grow for the construction industry as the drive for Digital Transformation starts enabling new players to dislodge established players in the industry. However, the IT industry typically lacks deep industry domain knowledge and this offers opportunities for construction professions to adapt and take advantage of the industry transformations that are emerging.

3.4. Developing in-house capability in affordable ways

Given the poor uptake of the UK Government's R&D Tax Credits, the role of Degree Apprenticeships, a new model for undergraduate education in the UK, could be a way to bring new digital capability to the construction industry. However, universities have been in a 'chicken and egg' situation as they need to prove demand for new courses exist before winning internal funding to develop them, and the evidence so far has been 'thin on the ground'. The UK Government is trying to help in this with funding being made available for courses that can make a difference (e.g. Digital Construction). The root problem remains though, the industry to date has not embraced digital transformation with the same enthusiasm as other industries (e.g. Manufacturing and "Industry 4.0"), as proven by the uptake of R&D Tax Credits.

At the same time we are seeing the open source and hacker communities inventing low cost IoT solutions. The authors are involved with the roll out of LoraWAN in Sheffield with the popular open source approach called The Things Network (TTN) [39]. The theory is that by having a free to use low powered radio wave based communication network across a city, the idea for companies to start developing IoT solutions becomes more feasible. If an open data approach is adopted then new sources of insight might become available such as enabling small construction companies to form real-time buyer clubs and enjoy better economy of scales. In a holistic sense, the idea of a smart city's digital layer opens possibilities for inquisitive construction companies seeking information advantages but this requires a mind-set that rises above the pursuit of productivity gains within the context of how things work today.

IoT solutions need not be very expensive and most cities have a hackspace with enthusiasts who can help. Today, you could buy a temperature sensor for about GBP £1 (e.g. Dallas 18B20), cheaper if you buy more than one. The sensor could be managed by a Wi-Fi enabled "System on a Chip" (SoC) for about GBP £2.50 (e.g. ESP8266) that has about 40 MB memory.

To get data from the sensor you could download a free open source message broker (e.g. MQTT) and install it on a Raspberry Pi which would cost about GBP £15. This could act as a gateway for multiple sensors to link via an internet connection to a server or cloud that has a dedicated database in it.

The sensor data is published to MQTT and your database subscribes to MQTT messages. The free database might be PostgreSQL or MYSQL and you could run it on a PC if the data volumes are not expected to be massive.

Having timestamped data in a database means you can enable analytics such as Machine Learning that continually updates a Linear Regression model you've created to predict the temperature later in the day (Tensorflow is a popular choice for Machine Learning and Artificial Intelligence libraries, which is again free and open source).

The point here is that IoT is accessible to even very low-cost budgets depending on basic coding skills being present. A bigger ambition to integrate different types of data will probably need a cloud and help from an IT company. If a construction company does not have any in-house understanding of even simple IoT solutions then they will probably struggle to judge value for money from an IT firm. Companies such as Amazon Web services, IBM, HPE, GE and Microsoft to name a few, have moved much of the IT complexity into a Cloud and have created IoT platforms as a service model.

3.5. IoT platforms

An IoT Platform includes integration of hardware, Operating Systems, virtualisation and often with IoT enablement such as MQTT, DDS, Kafka, Cassandra, Tensorflow etc., already built in. If real-time analytics is needed then some of the database (i.e. persistent storage in a DB) could be of the fast NoSQL variety such as Cassandra or Mongo. These NoSQL types of DB are typically columnar database (Neo4J is a graph DB), as opposed to traditional SQL DB, which is row and column therefore with slower data indexing and retrieval performance.

In a cloud, it is also possible to access and combine data from other sources such as email, ERP systems and other large data driven applications running across an enterprise through data virtualisation and an Application Programming Interface (API) that lets data from one application be ingested into another.

All these innovations and their combination open the way to valuable insights such as ways to achieve productivity improvements by removing previously unnoticed impediments. Much of the underpinning technology comes out of the open source community with most cloud instances running on open source "Cloud Foundry". Cloud services bring many advantages to consumers of IT and should be investigated by companies considering an IoT strategy.

As we have seen a move to converge IT and OT, we have also seen IT and cloud services mature and IT companies specialising in one or more layers of:

- Business Process as a Service (BPaaS): applications embedded in workflows allowing automation to be integrated with physical work.
- Software as a Service (SaaS): software and applications that operate on top of a platform such as SalesForce.com to manage demand creation and sales leads across the enterprise.
- Platform as a Service (PaaS): the virtualised infrastructure with other Middleware offered by IT companies typically trying to sell cloud services.
- Infrastructure as a Service (IaaS): the underpinning physical computing resources often including a public or private cloud.

At the base of the ecosystem is the foundational infrastructure and physical hardware (i.e. 'tin and wire') we think of, such as racks of blade servers with lights flashing, cabinets with thousands of wires hanging out of them, Local Area Networks (LAN), antenna etc. This can be bought as Infrastructure as a Service (IaaS).

On top of this is a platform layer which links all the infrastructure components together in a virtualised way through software. For example, a physical LAN in the infrastructure layer can have a software version called a Virtual or vLAN in the platform layer. Whilst the capacity of the physical foundational hardware cannot be exceeded, the software equivalents enable higher availability through built in redundancy. The combination of physical and virtualised infrastructure is at the heart of Software Defined Networks, Clouds, Elastic Compute and so on.

For some applications that sit on top of the Platform layer, you can buy them as Software as a Service (SaaS). In the past an IT company would get a lot of funding to develop a bespoke application and years later deliver it. We have all heard the stories about a massive new application deployed in the likes of the UK's NHS which failed to live up to expectations. SaaS overcomes such problems but the trade-off is you have to work with the imposed logic embedded in the SaaS offering if cost minimisation is a key requirement.

BPaaS builds on capability enabled in lower layers and provides a way for developers to build applications that automate and augment workflows. We have experience of solutions that use Augmented Reality (AR) to help field operatives fix equipment they have no experience of by using their mobile phones to overlay real-time diagnostics and instructions to open machinery and replace defective parts. We also have experience of solutions that use Virtual Reality (VR) to help operatives understand hazards in a physical location they have not yet visited.

There are lots of IT companies trying to sell cloud services and IoT linked to them. There are at least 450 IoT Platforms [40] to choose from so the buyer has significant economic-bargaining power. This manifests as a problem as each vendor tries to lock customers into their IoT platform by encapsulating data. In one laser cutting company we visited they had three machines from different suppliers and were locked out of data from those machines. We had to investigate developing a video analytics solution to enable better factory floor job scheduling. Key to advances in analytics has been progress made in Artificial Intelligence and Machine learning.

3.6. Artificial Intelligence and Machine Learning

A resurgence in Artificial Intelligence and Machine Learning seems to have accelerated out of innovations such as “Hadoop” [41] with algorithms such as “Map reduce” [42] becoming available from the open source community. This led to a widespread recognition of value from data mining across multiple sources and stimulated the emergence of Big Data [43]. The authors experienced performance issues with Hadoop when used in very large scale Big Data solutions [44] and so used it as means to store a Data Lake which could function more slowly. This performance issue stimulated innovation that also marked an evolution of a data warehouse.

The idea of robotics and driverless cars has seen many advances in Artificial Intelligence (AI). For the purposes of this paper we will consider two classes of AI algorithms: supervised and unsupervised learning. At the heart of many new AI innovations are Neural Networks (NN) which can cope with ambiguity such as each brick being a slightly different dimension than the previous one.

Those NN that need to be supervised require some kind of process whereby an algorithm predicts an answer, gets feedback on whether it was right or wrong and if wrong tries again. A typical supervised AI algorithm is a Convoluted Neural Network (CNN). These are ideal where the programmer ‘knows’ what types of outcomes are right or wrong and so it becomes a matter of training the neural network.

Another type of NN are unsupervised AI algorithms. They simply run until they find some kind pattern which links one set of features (i.e. values stored in a column) with another. These are interesting because they do not need a priori knowledge (i.e. no prior assumption of what is being looked for). They will find associations but the human must then find a way to describe them so others understand the implied causal relationship found in the data. A typical unsupervised AI algorithm is a Recursive Neural Network (RNN) and given sufficient data, new causal patterns could be recognised.

Essentially, a NN is a matrix of nodes in hidden layers each containing some form of a differential calculus equation. They have a way of storing optimised values that associate an input with an output. Once this optimised matrix of values is found and proven, then the ‘solution matrix’ can be pickled (i.e. frozen so no subsequent calculations are needed) and used on edge devices thus minimising the overall cost of compute (i.e. Once the compute intensive work is done in a data centre a pickled solution matrix is then deployed to different edge locations).

From Machine Learning to Convolutional Neural Networks that need supervised learning to Recursive Neural Networks that train themselves, the capability of computers available to construction is vastly higher today than say 24 months ago. Companies such as Google have given advanced Machine Learning and AI libraries to the open source community in products such as Tensorflow. Microsoft have also given their Cognitive Toolkit to open source. Because of the open source ‘gifts’ we can expect to see innovative applications based around predictive capability to not only grow in number but also tackle challenges many of us never thought computers could tackle; for example, matching the complexity of a task to Suitably Qualified and Experienced Personnel (SQEP) to better utilise varying levels of scarce expertise. A downside to making more and more data available has been exposure to security vulnerabilities and privacy issues.

3.7. Security and privacy

With millions of sensors, actuators and other devices combining to make an Internet of Things, the role of security and privacy become more important for companies and their reputation as trustable entities. Eastwood [45] sums this up saying:

> “Ten years ago, most of us had to only worry about protecting our computers. Five years ago, we had to worry about protecting our smartphones as well. Now we have to worry about protecting our car, our home appliances, our wearables, and many other IoT devices.”

Some companies have gathered information on their employees and sold it on to third parties [45] which not only raises privacy issues, but also ethical issues flowing from corporate responsibility. The challenges are not singularly technical in nature.

Network Authentication and control of who and what is on a network is important as is security and privacy around the data passing through the network and held in storage. Samani [46] told of malware infected high-risk pregnancy monitors at a hospital in Boston, USA. One risk is about proving a device is safe before it is allowed access to OT and another risk is about checking it is still safe once authentication and network access has been achieved. Companies not updating their firmware to deal with emergent vulnerabilities is a key concern as they could open a door to criminal hackers.

Europol [47] saw threat sources coming from two main origins: “*Crime-as-a-Service* and *anonymisation.*”

Crime-as-a-Service is where criminally-intent software can be purchased such as a “Denial of service” program. Anonymisation is where a TOR (The Onion Router) network hides the IP address of the end-user so they cannot be traced. This is sometimes called “The Dark Web”. It is similar to a VPN (Virtual Private network) which first makes a path through the internet then notes the router addresses before creating an encrypted ‘pipe’ through them.

Europol [47] outline rising sources of cybercrime as:

- Criminal marketplaces using anonymous payment mechanisms with crypto currencies (e.g. bit coin)
- Money laundering
- Malware that is rapidly increasing in scale and sophistication
- Ransomware
- Banking Trojans
- Controlling botnets

A number of threats, such as “man in the middle” attacks [48] can be minimised through security protocols. A man in the middle attack is where a criminal mimics your authentication credentials and then interacts with say your bank as if they are you. Public-Private keys in Secure Shell (SSH, [49]) are frequently used to avoid such vulnerabilities. A popular type of key, which is really an algorithm, in SSH is RSA (stands for the inventors' names, Rivest, Shamir and Adelman).

Some companies also provide Format Preserving Encryption (FPE, e.g. Voltage, [50]) This approach keeps the word format, but encrypts it and again relies on Public-Private keys to unencrypt it. A trivial example might be, “Sheffield is great” is encrypted to “X6alu9f5s 7d kwz4p” and sent over insecure communications. If a criminal intercepts this message it is of little use to them. This solution is particularly attractive for edge devices such as a sensor that needs to broadcast to a gateway over say Wi-Fi.

With billions of devices seeking access to networks, one promising technology to manage network authentication and verification is “Blockchain” [51] which was discussed above in another use-case.

To conclude this section, we see five key considerations:

- All device firmware to be regularly updated to deal with new vulnerabilities.
- Public-Private keys using SSH and something like RSA to check authentication and veracity.
- Format Preserving Encryption for edge of network communications so that sensitive data cannot be meaningfully intercepted.
- Blockchain to become a way to manage large scale authentication and verification (A potential business opportunity for a trusted provider)
- Ethical standards and Corporate Responsibility to ensure employees and others can trust employers

4. Innovation adoption in construction

In the previous section we showed many examples of how IT and OT are both evolving and converging. In this section, we will bring a keener focus on how that might play out for the construction industry.

Innovative solutions and visions are available to the construction industry. However, the key challenge the authors infer from the literature and conversations with people working in the industry is that most construction companies do not see themselves in an evolutionary process and behave as if digital innovation will not really impact them. That is, the case for change has not yet been agreed amongst most leaders in the UK construction industry, so they are not adapting (the authors called this a Block Buster strategy). The dominant uncertainties are productivity, costs, quality of work, labour and skills management, as well as health & safety, are just a few of the opportunities IoT could target. These need to be considered in a longer term strategy so a firm adapts in ways that enable it to prosper in the next phase of the digital evolution that will change many aspects of society.

It is feasible for new ways of organising skilled labour in flat organisations with low overheads to become economically powerful such as demonstrated by neighbourhood nurses called "Buurtzorg" in Holland. They started out with 8 nurses and 5 years later had 80% of the Dutch market [52]. A new application that coordinates construction labour and has a trusted payment mechanism, for example an application that uses Blockchain, could present a new way of organising a labour that competes with old fashioned hierarchical firms carrying lots of overheads. Trades could start to self-organise with help from such a coordinating application that finds the best blend of skills and availability, tradesman reputation, materials needed, delivery organised, automated documentation, automated billing and use their collective economic power to buy materials at a lower cost than builders merchants typically sell at so they have a cost advantage? That is, have lower overheads than traditional construction firms and enjoy economies of scale when purchasing materials and equipment.

4.1. Evolution of IoT in construction

Some construction companies are already visionary. For example, Balfour Beatty [53] recently published their vision for a human-free construction site by 2050. It shows a number of technology-instances (e.g. drones, robots, 3D printing etc.) but seemed to lack a view of how integrated data could link things together to unlock even more potential. They could have widened their peripheral vision to explore a larger strategic context for buildings in the rise of mega cities as the global population nudges closer to 9 billion. How could a construction company and IoT adapt the way 'construction' could interact in this new emerging era?

We believe game changing ideas come out of a gestalt between technology-instances and the transcending technological waves percolating outward [25]. However, the few visions we've seen from construction seem to be formed with an awareness of impending 'change resistance' and a need for quick Return on Investment (RoI). That is, the view of 2050 seems 'safe' rather than 'aggressive' given most of the technology in the visions already exist. We believe the construction industry's 'conservatism' could be seen as an opportunity for other more adventurous and technically savvy companies to 'disrupt' and those disrupters might come from outside the established players in the industry as manufacturers and offsite construction enter onsite assembly. Laing O'Rourke is different to most of their peers and investing heavily in Digital Engineering and offsite construction [54].

4.2. An evolutionary view of digital construction solutions

An evolution of IT innovation is easy to see in the field of construction. Zhong et al. [55] used IoT in prefabricated construction. Comparing this paper to an earlier paper with a similar focus by Yin et al. [56] we can see an evolutionary process has unfolded from an RFID centric focus to an IoT focus which combines different sources and types of data.

As data integration holds the key to future value creation, we must overcome a tendency to prefer point solutions that make data retrieval for different applications difficult. In 2007, Tatari et al. [57] reviewed construction enterprise information systems and make the 'point solution' perspective easy to see:

> "A total of 48 per cent of the firms use enterprise resource planning packages, but only 4 per cent of these firms chose to implement the project management modules that are commercially available."

More holistic views of what is possible can also be seen in the literature. Pena-Mora and Dwivedi [58] discussed collaborative messaging platforms and real-time information sharing was studied by Bowden, Dorr, Thorpe and Anumba [59]. Independently, workflow-management was studied by Son, Park, Kim and Chou [60]. The business value of better decision making on site would now be possible with an integrated IoT solution which uses more technically advanced solutions (e.g. open source Kafka enables the simultaneous copying of data streams to multiple destinations such as a data base or analytics engine, almost like a software defined message bus).

Bar-code and Personal Assistants were studied by Tserng et al. [61], and Chen and Kamara [62] discussed a framework for mobile computing on construction sites. Because of innovations such as Cloud Compute, what was previously only possible through standalone 'point solutions' can now be part of a more integrated solution using Application Programming Interface (API) possibilities to share data between applications in a SOA design.

RFID was studied by Ju, Kim and Kim [63] as part of a material delivery system. Wang [64] looked at RFID as part a quality management system. Montaser and Moselhi [65] used RFID and 'received signal strength' as a proxy for distances to locate people and materials inside buildings using Ultra High Frequency (UHF) radio waves. Cai et al. [66] achieved a similar ambition using GPS outside a building. The ingredients for an IoT ecosystem are known in the construction industry. What is often missing is a bold vision that creates a synthesised possibility which stands on top of well curated data that makes mining and using it in new applications easy to achieve.

We have also seen advances in robotics. Chu et al. [67] discuss robot based construction of steel beam high rise. Chu et al. also warned of problems from change resistance. As pointed out in earlier sections, history shows that society is often reconfigured by 'disruptive technology' and so any notion of change resistance is inextricably tied to wider societal factors. Both socio and technology is a unified concept, like different sides of the same coin.

We must not forget that IoT also brings advantages to other industries and so why wouldn't we expect steel makers to also be steel erectors if they can automate work thus making site based coordination easy to be achieved? Later we saw Tan, Mohan and Watanabe [68] discuss a framework for robot-inclusive environments. Again, the technological evolution is easy to see.

Lipman [69] studied Virtual Reality Modeling Language on handheld devices. At that time it was hard to ensure smooth visual transitions on an edge device (e.g. a mobile device) as when a complex CAD model was turned it required millions of calculations that would be hard to perform on a thin client (i.e. small compute power available inside a mobile device). The usual way was for an edge device to be remote from the main workstations with their own back-end compute cluster in the data centre. If the distances between the edge device and the data centre were long (we increasingly struggled with distances over 200 miles) then network lag also led to 'jitter' as rendered images were presenting on the edge screen. To minimise the network effect technologies such as "WAN Accelerators" (e.g. SteelHead) were used to speed up data transmission and caching solutions to hide delay from the end user. Since then, advances in high-end graphic cards, typically using NVIDIA innovation, have emerged out of the gaming industry and technologies such as HPE's "Remote Graphics Software" (RGS, [70]) transmitted changed pixels only, rather than fully rendered frames. What was a big problem say five years ago is no longer the impediment it was.

Lee et al. [71] used different types of sensor as part of safety management solution detecting falling objects. The raw ingredients for IoT solutions are in place and have been used. This is important to acknowledge when considering potential change resistance from an industry that prefers proven technology.

Wu et al. [72] talk about real-time tracking of near-miss accidents using RFID and Zigbee as the radio based communication method. This is also close to what could be described as an IoT solution; things at the edge (e.g. humans wearing RFID tags) communicating to a core (i.e. in their use case the edge nodes talk to a local server and that server could have been integrated with other cloud based solutions such as health monitoring).

Situational awareness using GPS, wireless and web technologies was discussed by Oloufa et al. [73]. This has many features that could be viewed as close to IoT. We only have to look at IoT in the automobile industry and "Connected Car" [74] to see how ideas like this have evolved and show the promise of a new computational architecture based around distributed compute, storage and swarm analytics [75].

The most important need is to reflect on how the construction industry has engaged IT led innovation previously. As discussed above, the story of IT through to IoT is a journey from point solutions (e.g. a material management solution) that independently targets a specific business problem (e.g. material inventory levels) to one that sees integrated data from many different sources (data linking materials management to productivity and weather conditions) as the source of valuable insights (i.e. an ecosystem that enables a digital layer).

Those construction companies that do not embrace IoT or Industry 4.0 or the Industrial Internet or other digitisation approaches will experience increasing levels of competition and profit squeeze as being undifferentiated they become customers' second choice behind tech savvy rivals.

Companies that ignore the digitisation phenomena will be pushed further into low-tech labour-intensive context and others that also fail to adapt will join them to make this a highly competitive, low margin segment. To deny progress is a strategy at odds with the transformation of a construction industry set to become a more high-tech capital-intensive industry.

A step closer to a digital layer can only be achieved if all participating companies in a major capital project shared their data so that the construction industry could get closer to the manufacturing industry in terms of range of data types to feed into AI and ML. For this to happen, new approaches for BIM are necessary as it moves from a federated to an integrated approach to data driven insights.

4.3. The evolution of BIM

Interestingly, Building Information Modeling (BIM) with its origins in CAD evolved in parallel to IoT. BIM is essentially an object-oriented software approach to data exchange through federated databases. Whilst this was in of itself a big step forward it was limiting future possibilities and one only has to see new solutions such as Autodesk's "Dasher 360" to see how sensors and IoT are creeping into the world of BIM.

By combining IT innovations, it is now possible to create a virtual copy, a "Digital Twin", of a physical 'thing'. Taking telemetry data from the sensors at the 'edge' of a network that are embedded into a thing, it is possible to run real-time simulations on a Digital Twin in the 'core' of the network, if network speeds can deliver the performance needed. We would know a lot about a specific thing (e.g. a power generator) such as what specific parts it is made of, what batch they came out of, when it was last inspected for maintenance and so on. If we see a problem with say a bearing, we would know which other things (e.g. other power generators) have a bearing from the same batch that whilst showing no problems, might be about to. We are no longer reacting to events, we are anticipating them and so can adapt our management plans accordingly. This possibility needs to be physically 'built' into the building's components and here is a clue to new service models and new service management offerings we might see emerge out of the construction industry.

The Digital Twin is a revolutionary idea for maintenance as it means they can move from reacting to events to predicting them. Advances in Machine Learning and Artificial Intelligence can take this to an even more profound set of possibilities as the implications of one asset failing and its consequential effect on other assets, can be modelled and predicted in order to asses criticality to key strategic objectives. For example, of the 50 things that need fixing today, what one if fixed first would create most value for occupants and other stakeholders?

The manufacturing industry have a similar concept to BIM they call Product Lifecycle Management (PLM). As sensors were added we saw PLM [76] evolve to become the Industrial Internet or Industry 4.0 which are collections of standards, some still emerging and evolving. The key difference between BIM and PLM is the ability to 'integrate' other data types from Corporate IT's "Systems of Records" such as Enterprise Resource Planning (ERP) and Manufacturing Execution System (MES) data from across the whole lifecycle. This difference probably stems from the fact a specific manufacturer owns much more of the end to end lifecycle and its data than any single actor in a highly fragmented construction industry does.

If we view Building Information Modeling (BIM) as a type of Product Lifecycle Management (PLM) ecosystem, both types of ontological engineering [76], then we can expect to see closer ties between BIM and Industry 4.0. By using common standards, we reduce connectivity problems and enjoy more choices in the solutions we can select to install in 'our' ecosystem as other developers create new offerings to an Industry 4.0 standard.

5. Future research and discussion

By understanding existing literature over time is mapping how a socio-technical complex is itself evolving, we can begin to anticipate new ways of conceiving an adaptable built environment that is dynamically responsive. This responsiveness could be within a building and based around dynamic usage such as a bedroom being transformed into a home office at 9.00 am and later reverting back to a bedroom. Such adaptability could also happen outside a building such as hydroponics combined with moving sun screens to help manage cooling and food production. A smart city with benefits of digital integration and a transcending digital layer requires construction companies to 'evolve' in that direction, and so prefer solutions that embed them more in a digital ecosystem than trap them in silo caused by single point solutions.

We believe construction companies need help to better understand the issues and opportunities with various technologies in the context of an evolving and strategically wider Enterprise Architecture strategy [32,77]. We also believe more research is needed into the numerous issues (i.e. socio-technical, organisation design, change management, etc.) construction companies will face if they decide their long term survival is contingent on digital transformation. We believe this large agenda is necessary to explore because the Fourth Industrial Revolution is already established in many manufacturing industries (e.g. the automotive industry and 'connected car') and its influence will enter the construction industry in one form or another. We see the following areas for future research:

- A deeper understanding of why the UK construction industry is not more active in digital R&D.
- The role professional bodies play in building digital skills as part of their accreditation processes.
- A needs analysis of smart cities that translates into creative solutions the construction industry could provide.
- A digital strategy review based around the possibilities enabled by open source, open data with links to open technology and how the construction industry could enable it

Our insight from the literature review is that we are in an evolutionary process. Our discussion of Kondratieff and Schumpeter, helped us to see there is a repeating pattern throughout history, much older than any notion of four waves encapsulated within the idea of "Industry 4.0". Schumpeter's idea of 'Creative destruction' also helps us understand why many established organisations fail to make the leap to new societal configurations, most downfalls driven by some form of disruptive technology or other that was underestimated.

Just as Uber and Airbnb used creativity to see how new information flows can move economic power in an established value chain, seeing the construction industry in the context of an ever adapting smart city driven by a digital layer opens new strategic possibilities through data and information flows. A concern here is that given a lack of widespread R&D activity in the UK construction industry, despite the government offering R&D Tax Credits, suggests most construction industry leaders have yet to deeply believe the case for digital transformation exists.

Even if leaders do realise now is a time to adapt and evolve, transformational change for large established companies is not easy as remuneration systems are often locked into old ways of thinking. Smaller and younger companies with access to funding may be able to adapt and adopt new ways of thinking much easier than established, older and more rigid hierarchical companies that tend to struggle with disruptive innovations.

The leap from 'low-tech labour intensive approaches' to 'high-tech capital intensive approaches' in construction will be difficult. Notions such as "Return on Investment" are surrounded by a lot of uncertainty which makes investment appraisals hard to reliably quantify. This too has been played out in other industries as our discussion of Netflix and Blockbuster Video points out. Those construction firms which do not invest in developing the capability to transform are at a higher risk of not making the leap to a future which is connected to digital layers that overarch smart cities.

To better navigate an evolving context driven by disruptive technologies, it is also important to see current behaviours may be undermining the ability to adapt and take advantage of new possibilities such as seen by an IT firm that owns Google, Alphabet, becoming a property developer.

Many companies simply try to 'tweak' what they do today using innovative automation to make the same things in the same ways 'faster, better, cheaper, and safer' which reinforces a preference to buy point solutions. The main problem that follows from the procurement of disparate point solutions is the data becomes inaccessible to other solutions in an era where we are heading towards data driven decision making. To minimise this risk an enterprise architecture strategy and road map become even more important and they too must see their own evolution in a digital layer that transcends smart cities.

The future may see new entrants to the industry pursuing ideas of process automation. We are seeing the manufacturing industry moving into the construction industry such as the Semi-Automated-Machine (SAM) made by Construction Robotics of New York, which claims to lay about 3000 bricks per day for USD $3300 per month [78]. As SAM exists today, this is a reality and not some fanciful aspiration of the future.

Another key insight is that new skills are needed and should be encouraged to evolve. Construction professional with IT knowledge will be differentiated from those that have none. This represents both an opportunity if adaptation is favoured and a threat if stuck in old ways that become uncalled for. It is not clear where these new skills will come from and perhaps this is an opportunity for the UK Government to incentivise academia to develop courses ahead of clearly defined demand signals from an intransigent industry.

It would be easy to infer a lack of change in the UK construction industry is due to a culture of "risk aversion". The reasons must be deeper and should be researched to untangle what is holding the majority of UK construction companies back from trying digital experiments that shed light on the possibility of new business models and new sources of revenue. The point is, the case for change is here whether it is recognised or not.

6. Conclusions

In this paper we set out to achieve a number of objectives.

- We have set the scope of this paper as a wider view of transformational socio-technological processes in society.
- Within this we have established a link from the evolution of the UK construction industry to the evolution of the Built Environment and used the idea of a 'digital layer' in a smart city to argue away from 'point solutions' to an 'ecosystem' view.
- We explained how the IT industry evolved faster than the OT industry and that their convergence is the frontier of new socio-technical challenges and opportunities.
- We explained how low level protocols present technical challenges as not all OT devices are "IP Addressable" and introducing TCP/IP or UDP/IP protocols presents security risks as Process Control Domain firewalls can be circumvented.
- We also outlined the contradicting outcomes of increased security as sharable data becomes more challenging from a security perspective.
- We have shown how future directions for digital construction need to evolve in an ecosystem architecture as is emerging in smart cities as a 'digital layer'.
- We discussed the evolution of point solutions drawn from the literature and used this to explain implications for an IoT enabled UK construction industry
- We made the case that IoT and digital construction itself will evolve in the context of smart cities or other transcending digital layers, as has been achieved in UK Defence.
- We also outlined future research directions as well as providing conclusions in this section to help construction companies to review how they currently view digital transformation.

Whilst it is hard to predict how the future will unfold we can see some trends that map a journey from today's 'point solutions' to a transcending digital layer that encompasses a large urban area's ecosystem:

- **A digital layer will emerge based around 'open data'** and transcend the built environment and all industries that play some kind of role in it such as will be the case for Smart Cities.
- **New entrants** will disrupt established players through a reworking of information flows (e.g. Uber). Many will emerge out of the manufacturing industry as they invent machines that replace scarce

site based skills (e.g. SAM) and we can expect more off-site fabrication that requires levels of complexity that are too hard to achieve on-site.

- **New 'smart' products** will emerge that provide greater insight into uncertainties that link to long term costs (e.g. Condition Based Monitoring of components in elevators driving maintenance work orders)
- **New services** based around data from sensors through a radio based technology (e.g. LPWAN) that link to real-time analytics engines to tackle problems such as asset tracking (e.g. A mobile phone alert showing a compressor we had delivered to site last week has unauthorised movement and is travelling down the highway)
- **New processes** that change workflows and use information flows to create more value (e.g. drones and laser scans used to measure production volumes several times a day and illuminate productivity problems for management).
- **New ways of working** such as every construction manager getting a list of the top 5 individualised issues they need to focus on in the next 24 h making task prioritisation more focused on key objectives. (e.g. data from the supply chain suggesting tasks for tomorrow are unlikely to happen due to problems off site and so a new site plan is automatically generated for the morning)
- **New expectations** as customers learn from other industries and demand the construction industry brings similar innovations (e.g. hybrid renewable energy solutions linked to a building's daily carbon footprint)
- **New business models** as some construction companies start selling 'Buildings as a Service' that is an IoT led evolution of PFI, without the need for a heavy reliance on contracts. In an IoT led "Design-Build-Maintain" approach, the contractor has a vested interest in long-term-low-cost maintenance with sensors shedding light on issues we have previously been unable to monitor (e.g. corrosion on steam pipes under an insulating wrapper). If the construction company owns the long-term maintenance costs, and are paid a constant monthly service charge, then they become incentivised to innovate to increase profitability (assuming service quality is not degraded).
- **New relationships** as IoT enables a long-term partnership between the customer and the construction company that provides a Building as a Service. Together, they plan service changes to adapt with the needs of the customer's business. In return, the construction company gets monthly revenue and a more predictable cash flow making their business planning less random.
- **IT and IoT security** must be regularly reviewed and assessed. A security breach may not only have immediate financial costs but also longer term ones as a damaged reputation leads to a loss of trust and confidence from customers and employees.

To close our conclusions, we have seen several evolutionary waves of strategic innovation many times before, and as Schumpeter points out with 'Creative destruction'. What is happening today has happened before. Many emerging trends are easy to see. We argue that existing UK construction companies must understand the changing context they exist and operate within and that they need to manage their own transformational adaptation to better fit with emerging strategic priorities (e.g. the role of data in the ever changing built environment of a smart city). Now is a time to invest in R&D with Government support. Those companies that do not adapt are unlikely to prosper or even survive.

Declaration of interest

Neither author has any financial interest or personal relationship with any person or organisation cited and so do not believe there is any inappropriate influence on this work.

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