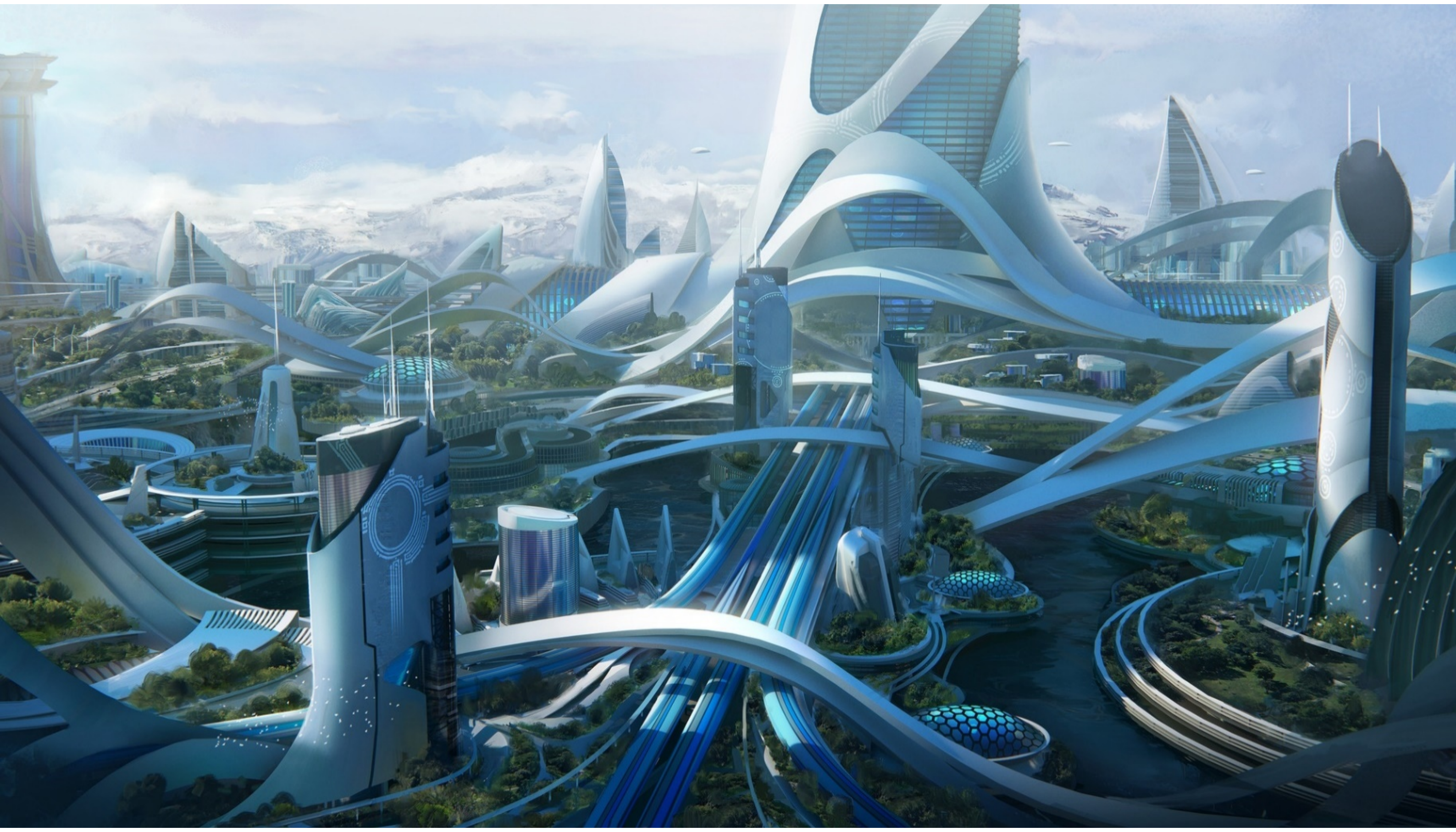
Built Environment Futures



Paper 1: Construction

In Association with:

Foreword

At Robertson our vision for the future is to 'assure a sustainable future'. By this we mean we will work to ensure profitable growth which builds on a strong customer focus, consistent and predictable construction delivery, investment in our people, partnership with our suppliers, and adoption of new technology.

To ensure we were 'future-proofing' our business and operational strategy we identified a need to have a look further ahead to 5, 10 and 20 years down the line to understand how our customers and markets are likely to change. This in turn allows us to consider the impact or opportunity for our businesses and respond accordingly.

We were pleased to find willing collaborators in this endeavour in Autodesk, Scottish Enterprise and the Construction Scotland Innovation Centre, all of whom helped fund this work. We commissioned Glasgow Caledonian University to carry out a series of three research papers looking at the Construction, Facilities Management and Infrastructure Markets. The views expressed in the papers are those of Dr Michael Tong and his team of researchers, but they have been guided by the steering group of partners. We are also grateful to Autodesk for sharing with us the time of some of their global experts.

Since the reports were commissioned, we have experienced the unprecedented circumstances of the COVID-19 pandemic which has changed the built environment sector overnight, accelerating the use of digital tools and reconfirming the importance of front-line Facilities Management staff. Although business challenges have changed in the short-term, the risks and opportunities the reports highlight are still relevant. Some, such as the desire to become more resilient through a net zero carbon economy and by using digital technology have come closer, whilst others may have become less relevant or are likely to move on a slower timescale. Nevertheless, we value the insight and challenge they bring to our business.

However, whilst we take time to consider how these inform our strategy and business models, we are keen to share this insight with the wider built environment. We hope you enjoy reading the papers and that they stimulate conversations in your organisations and with your partners about the opportunities they present for our sector.

Elliot Robertson
CEO Robertson Group

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Executive Summary

Visions of the future are dominated by methodologies such as horizon scanning and scenario planning that are adopted by government, think-tanks and corporations. However, these are predominantly about maintaining the status quo and about risk aversion. Interesting ideas or innovative speculations can often be overlooked. The construction sector is lagging behind other industries in terms of digitalisation, workflow integration and process optimisation. Construction projects today continue to be built in a very similar way to those of several decades ago: the bulk of work is still done on-site, with little automation and process optimisation. The sector has not fully entered the third industrial revolution, let alone the fourth. The main obstacles being the construction site itself, the fragmentation of the industry with the proliferation of SMEs and the lack of knowledge transfer. As a result, the construction industry has struggled to raise its productivity level and faces constant challenges in delivering projects successfully to the value metrics of quality, safety, schedule, winning work, and costs. The intention of this report is to promote a freedom to imagine futures that would exist for other reasons than corporate or governmental advantage. Some of the resulting ideas may seem fanciful but may have greater potential than more cautious projections. This report does not aim to provide definitive answers, instead, it encourages decision-makers to ask the right questions.

Section A provides the context for the research and proposes a four step approach for the effective implementation of digital transformation. First, the United Nations Sustainable Development Goals, specifically Goal 9 & 11, highlights how the construction industry has a significant wider societal role. Next, the four step approach is presented which aims to provide the foundation for the effective implementation of digital transformation, increasing the chances of success for the opportunities that are proposed in the ten key themes of this report. The first step is to reflect on the future of work. Step 2 is the need for reimagining construction. Step 3 is managing innovation portfolios more effectively and step 4 is to enhance digital transformation without unnecessary disruption. This approach aims to better engage with the themes identified in the future scenarios.

Section B is the core of this report and examines the key themes which we believe will have the most impact on the construction industry and are based on a critical review of the literature available. The themes are examined through the lens of the World Economic Forum's three Future Scenarios (*1.Building in a Virtual World, 2.Factories Run the World*, and 3.*A Green Reboot*) by highlighting key trends, their time horizon, and their potential impact. These Scenarios are very much becoming a reality and their influence will undoubtedly increase in the coming years. Scenario 1 is the one that will develop the most now (0-5 yrs) and in the next (5-10 yrs) time horizons. The technologies in the identified themes are all available but their application have been limited and connected workflows is critical to unlock its potential. Scenario 2 themes are making rapid progress in many sectors, driven by Industry 4.0. Recent development of industrialised approaches could see it flourish in the next (5-10 yrs) and future (10-20 yrs) time horizons. Scenario 3 needs to be considered at all three time horizons.

Section C provides a summary of interviews with subject area specialists from Autodesk on the Future of construction. Their individual expertise provides a fascinating and enlightening perspective.

This paper was brought together prior to the Covid-19 pandemic. The fact that all key themes identified are still highly relevant despite recent developments gives some assurances that the key themes will continue to be relevant. In McKinsey & Co's May 2020 report "How construction can emerge stronger after coronavirus", many of the themes discussed here are covered by both its identified short and long term trends as well as its proposed set of actions for success.

This initial section provides the context for the research and proposes a four step approach for the effective implementation of digital transformation to better engage with the themes identified in the future scenarios in Section B of this report. First, the United Nations Sustainable Development Goals, specifically Goal 9 & 11, to highlight how the construction industry has a significant wider societal role. Next, the four step approach is presented which aims to provide the foundation for the effective implementation of digital transformation, increasing the chances of success for the opportunities that are proposed in the ten key themes of this report. The first step is the future of work. Step 2 is the need for reimagining construction. Step 3 is managing innovation portfolios more effectively and step 4 is to enhance digital transformation without unnecessary disruption.

1. United Nations Sustainable Development Goals

The Sustainable Development Goals are the blueprint to achieve a better and more sustainable future for all. The 17 Goals are all interconnected and address the global challenges we face, including those related to poverty, inequality, climate change, environmental degradation, peace and justice. In particular, Goals 9 & 11 act as a reminder for the Construction Industry of its pivotal role in society. A number of organisations, such as the Robertson Group supports and endorses the UN Sustainable Development Goals to redefine their Responsible Business Policy, focusing on how best to respond to material issues within the Global Goals at local level. They focus on sustainability by being socially, economically and environmentally responsible in all their operations as this is crucial to the success they have achieved to date and to the continued sustainability of their business.

GOAL 9: Industry, Innovation, and Infrastructure
Investments in infrastructure (transport, irrigation, energy and information and communication technology) are crucial to achieving sustainable development and empowering communities in many countries. It has long been recognized that growth in productivity and incomes, and improvements in health and education outcomes require investment in infrastructure. Technological progress is the foundation of efforts to achieve environmental objectives, such as increased resource and energy-efficiency. Without technology and innovation, industrialisation will not happen, and without industrialization, development will not happen. There needs to be more investments in high-tech products that dominate the manufacturing productions to increase efficiency and a focus on mobile cellular services that increase connections between people.

GOAL 11: Sustainable Cities and Communities
Cities are hubs for ideas, commerce, culture, science, productivity, social development and much more. At their best, cities have enabled people to advance socially and economically. With the number of people living within cities projected to rise to 5 billion by 2030, it's important that efficient urban planning and management practices are in place to deal with the challenges brought by urbanization. Urbanisation bring about challenges in maintaining cities in a way that continues to create jobs and prosperity without straining land and resources. Common urban challenges include congestion, lack of funds to provide basic services, a shortage of adequate housing, lack of sustainable transport systems for all, declining infrastructure and rising air pollution within cities.

2. The Work of the Future - Step 1

A Task Force on the Work of the Future[1] consisting of key stakeholders from industry, academia, education, labour and philanthropy was recently established at Massachusetts Institute of Technology (MIT) to try and understand the relationships between emerging technologies and work, and to explore strategies to enable a future of shared prosperity. The findings from the Task Force suggests that in the last four decades, even if technological advances deliver rising productivity, there is no guarantee that the fruits of this bounty will reach the typical worker and the uncertainty is greater still for women and minorities. These discouraging facts may help to explain why a substantial majority of people believe that emerging technologies will magnify inequality and make high-paying jobs harder to find.

The Task Force identified a constructive path forward—grounded in evidence of what is happening today, deploying expertise in technology and the social sciences, and applying reasonable assumptions and extrapolations to anticipate what might happen tomorrow. There preliminary findings indicated that in prior eras, mechanisation and automation eliminated much undesirable work, while creating substantial new and more desirable work, and simultaneously raising productivity and enabling higher living standards. In their assessment, the current era is different in two respects: employment polarisation and 'so-so' technologies.

A **first distinction** between past and present is in how digital technologies reshape the division of labour between people and machines. The era of mass production created vast new earnings opportunities for blue-collar workers in factories and businesses, while simultaneously opening new vistas for skilled workers in white-collar work and the professions. As did earlier waves of automation, the current era of digitalisation also complements highly-educated workers possessing expertise, judgment, and creativity. Digital automation tended to displace *middle-skill* workers performing routine codifiable tasks, such as sales; office and administrative support; and production, craft and repair occupations. Ironically, digitalisation has had the smallest impact on the tasks of workers in low-paid manual and service jobs. Those positions demand physical dexterity, visual recognition, face-to-face communications, and situational adaptability which remain largely out of reach of current automation but are readily accomplished by adults with moderate levels of education. As middle-skill occupations have declined, manual and service occupations have become an increasingly central job category for those with high school or lower education. This has created labour market polarisation: simultaneous growth of high-education, high-wage and low-education, low-wage jobs at the expense of middle-skill jobs.

A **second key difference** between the era of digitalisation and earlier eras is that digitalisation has *not* delivered the same gains in productivity. It seems counterintuitive that so many kinds of workers such as cashiers, machine operators, secretaries, and administrative assistants and many more could be losing their jobs to disruptive technologies, without producing measurable gains in productivity. This paradox is due to the effects of **substitution** and **complementarity**. When a new technology automates a set of tasks previously done by workers, it *substitutes* machinery for people. This process raises aggregate productivity to the extent that the machinery is cheaper, faster, or better at the tasks than the workers who previously performed them. Substitution of machines for workers creates

[1] Autor et al. (2019) The Work of the Future: Shaping Technology and Institutions, MIT

winners and losers with gains typically flowing to firms via higher profits and to customers via lower prices. The costs, however, are typically borne by displaced workers, their families, and their communities, as well as by the public.

Automation and new technologies may also complement and often *augment* workers' productivity in their current job tasks rather than displace workers from those tasks. Examples include power tools that equip construction workers to accomplish more in less time and computer aided design (CAD) software that allows architects to rapidly explore design options without painstaking drafting. These labour-complementary technologies also raise productivity. In contrast to labour-substituting technologies, however, complementary technologies tend to increase earnings because they render workers more effective in their existing job tasks. They also frequently change the nature of the work and enable new capabilities. Because productivity gains often lead to lower prices, improved quality, or greater convenience, employment of workers performing these tasks may rise. Technologies that disrupt employment and displace workers without generating much of a boost in productivity are labelled "so-so". The 'so-so' nature of some digital innovations may help explain the paradox of sluggish productivity growth accompanied by considerable labour displacement. Not all digital innovations are so-so, and some have extraordinary productivity benefits but these innovations tend to complement the labour of highly educated professionals. Conversely, digital technologies affecting workers outside these elite ranks may displace non-college workers from clerical, sales, production, and operations occupations—shunting them toward in-person services that typically require generic skill sets and offer low wages.

With concerns about automation rife, there is a need to reframe the situation. We could reframe the threat of automation as an opportunity for augmentation. Davenport and Kirby[2] explored this augmentation strategy. It stands in stark contrast to the automation strategies that efficiency minded enterprises have pursued in the past. Automation starts with a baseline of what people do in a given job and subtracts from that. It deploys computers to chip away at the tasks humans perform as soon as those tasks can be codified. Augmentation, in contrast, means starting with what humans do today and figuring out how that work could be deepened rather than diminished by a greater use of machines. They propose a change in mindset, on the part of both workers and providers of work that will lead to different outcomes. A change from pursuing automation to promoting augmentation. This seemingly simple terminological shift will have deep implications for how organizations are managed and how individuals strive to succeed. Knowledge workers will come to see smart machines as partners and collaborators in creative problem solving.

The obvious next question is what can be done about it? The Task Force argues against fatalism and in favour of tempered optimism. Better work and broadly shared prosperity are not assured but both are feasible, and technological advances make them more, and not less attainable. This report aims to build on the lessons learned from the collective experiences of automation in other sectors by focusing on current and emerging themes that have the potential to enhance the augmentation of our workforce to secure a sustainable and successful future for the Construction Industry.

[2] Davenport & Kirby (2015) Beyond Automation, Harvard Business Review, June.

3. Reimagining construction: The vision for digital transformation[3] - Step 2

Autodesk in association with CIOB (2019) produced a discussion paper that re-imagines the future for construction. It provides a vision of an industry transformed by the use of digital technology over the next 3 to 10 years, and lays out the key steps construction firms need to take to get there. It answers the key questions posed by construction leaders and managers responsible for strategy, business development, innovation, operations, projects, functions, technology and more. It is particularly relevant for those working for, or with, general contractors, smaller contractors and speciality trades.

Questions asked include:

- **What does a construction industry transformed through the use of digital technology actually look like?**
- **What are the most exciting technology trends for the next ten years?**
- **What is the roadmap: the key steps, in particular the first, needed to realise this vision?**

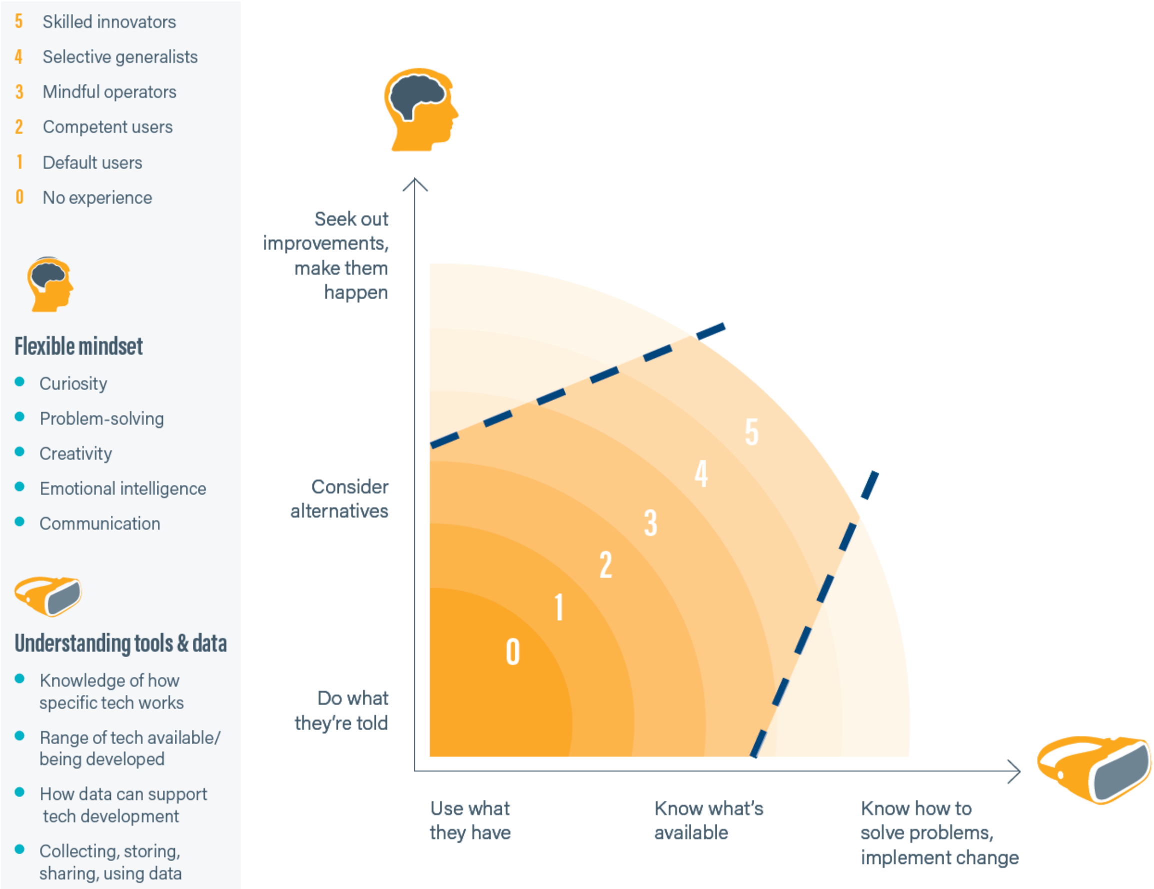
The transformative power of digital technologies such as robotics, machine learning, drones, the Internet of Things (IoT), and augmented reality are here already available for the construction industry to adopt. From AI-enhanced decision making on future work pipelines, to algorithms designing estimates, and big data powered scheduling – the implications are profound. The result will be a more profitable, resilient and agile industry, and a better built environment. Traditional barriers to project entry such as capital, knowledge, and efficiencies will crumble as digital technologies democratise and level the playing field, particularly for smaller businesses. But, these new digital tools will also open doors for new competitors from other industries to enter. For many, these changes can't come soon enough. By 2030, population growth, urbanisation and economic expansion are predicted to increase global demand for construction output by 85%. Rising complexity and risk, constrained finances, the skills gap, and growing sustainability concerns are already driving contractors to develop new ways of thinking about and delivering buildings and infrastructure.

The paper examines the why, what and how of digital technology. It details what the construction industry has to gain by adopting new digital technologies over the coming decade, and then gives examples of the specific technologies that can bring about these improvements. Finally, the paper provides guidance to contractors on the key steps to overcome the main barriers to adoption. By integrating digital technologies into the corporate strategy creates a solid top down approach, but it's

[3] Autodesk (2019) Reimagining construction: The vision for digital transformation and a roadmap of how to get there

likely employees and clients will, sometimes unconsciously, put up resistance. Key areas include: ***employee inertia, client resistance*** and the **current skills gap**.

The discussion paper highlights a CITB Research which groups these skills into two core competencies that are needed to push the industry forward: having a **flexible mindset** and an **understanding of tools and data**. It is not just the organisation who should take responsibility for upskilling the workforce, individuals must also take charge of their own upskilling.



Source: [CITB - Unlocking Construction's Digital Future]()

The key actions employees should consider are:
• Identify their basic skills needs
• Proactively drive their own professional development to include the skills needed for both a flexible mindset and digital technology and workflows
• Seek the required knowledge/skills appropriate to their role
• Seek opportunities where they can get involved – just do it, keep it simple and seek results
• Stay in the game – it's exciting and a whole new world of opportunity is opening up!

Unless the two core competencies highlighted above are put in place and serious considerations are given to the key actions then it will difficult for the majority of the potential opportunities identified in this report to be realised.

4. Managing Your Innovation Portfolio - Step 3

The research conducted by Nagji and Tuff[4] on *Managing Your Innovation Portfolio* provides a very useful strategy of viewing innovation in an organisation. The companies they found to have the strongest innovation track records can articulate a clear innovation ambition; have struck the right balance of *core, adjacent,* and *transformational* initiatives across the enterprise; and have put in place the tools and capabilities to manage those various initiatives as parts of an integrated whole. Rather than hoping that their future will emerge from a collection of ad-hoc, stand-alone efforts that compete with one another for time, money, attention, and prestige, they manage for "total innovation."

In a study of companies in the industrial, technology, and consumer goods sectors, they looked at whether any particular allocation of resources across core, adjacent, and transformational initiatives correlated with significantly better performance as reflected in share price. It was found that companies that allocated about 70% of their innovation activity to core initiatives, 20% to adjacent ones, and 10% to transformational ones outperformed their peers.

A second research finding focusing on more-direct returns on innovation showed that bottom line gains companies enjoy as a result of their innovation efforts found that the proportions of returns ratio generated by core, adjacent, and transformational initiatives is roughly the inverse of that ideal allocation. Core innovation efforts typically contribute 10% of the long-term, cumulative return on innovation investment; adjacent initiatives contribute 20%; and transformational efforts contribute 70%.

These findings highlight the importance of managing total innovation. Most companies are heavily oriented toward core innovation given the risk involved in adjacent and transformational initiatives. However, if that natural tendency leads to neglect of more-ambitious forms of innovation, the outcome will be a steady decline in business and relevance to customers. Transformational initiatives are opportunities for significant growth.

It is important to acknowledge that a 70-20-10 breakdown of innovation investment is not a magic formula for all companies. The right balance will vary from company to company according to a number of factors such as a company's competitive position within its industry. The point is that a management team should arrive at a ratio that it believes will deliver better ROI in the form of revenue growth and market capitalization, should discover how far its current allocation is from that ideal, and should come up with a plan to close the gap.

An Innovation System that targets a healthy balance of core, adjacent, and transformational innovation is a first step toward managing a total innovation portfolio. However, not many companies are good at all three with most struggling with transformational innovation. This reflects the hard truth that to achieve transformation—to do different things—an organization usually has to *do things differently*. It needs different people, different motivational factors, and different support systems. The ones that get it right have thought carefully about five key areas of management that serve the three levels of innovation ambition. These include talent, integration, funding, pipeline management and metrics.

[4] Nagji and Tuff (2012) Managing Your Innovation Portfolio, Harvard Business Review, May.

5. Digital Transformation by Minimising Disruption - Step 4

The term digital transformation simply means adapting an organization's strategy and structure to capture opportunities enabled by digital technology. However, it has become increasingly difficult for a company to translate that answer into an action plan and understandable that managers struggle to grasp what digital transformation actually means for them in terms of which opportunities to pursue and which initiatives to prioritise.

It is not surprising that many managers expect digital transformation to involve a radical disruption of the business and in some cases this may be required. However, the research by Furr and Shipilov[5] suggest that for most companies, digital transformation means something very different from outright disruption, in which the old is swept away by the new. Change is involved, sometimes radical but more often than not, transformation means incremental steps to better deliver the core value proposition. They also dispel five myths associated with digital transformation and provide the reality.

MYTH	REALITY
Digital requires radical disruption of the value proposition.	It usually means using digital tools to better serve the known customer need.

The shipping container company Maersk provides a good example of the first myth. The costs of shipping are affected by global trade barriers and inefficiency in international supply chains. The industry also suffers from a lack of transparency. These are familiar challenges. What digital did for Maersk was provide a new way of overcoming them. The company partnered with IBM and government authorities to deploy blockchain technology for fast and secure access to end-to-end supply chain information from a single source. The technology, coupled with an ability to receive real-time sensor data, allows trustworthy cross-organization workflows, lower administrative expenses, and better risk assessments in global shipments. This shift allows Maersk to serve its core customers better. But Maersk has not been transformed into Google. It remains a company whose value proposition is providing a fast, reliable, cost-efficient shipping service--one with the potential to be more streamlined and transparent, thanks to a smart leveraging of digital technology.

MYTH	REALITY
Digital will replace physical.	It's a "both/and."

Digital often enables the elimination of inefficient intermediaries and costly physical infrastructure but that does not mean the physical goes away entirely. In the energy sector, several electric utility companies in Europe have effectively combined the advantages of physical and digital in their connected home systems, which contain smart thermostats and a variety of sensors and detectors. Google and Amazon have entered the market for smart home devices, but utilities have the advantage

[5] Furr and Shipilov (2019) Digital doesn't have to be disruptive, Harvard Business Review, July-August.

of engineers (or selected contractors) who back the smart thermostats' value proposition and customers trust those people to do installation, maintenance, and repair. Some of these companies enable preventive maintenance: If a sensor indicates that a heating system is about to break, the customer is alerted through the thermostat and can schedule an engineer's visit in advance. The same alert helps the engineer understand the problem before the visit and arrive with the right equipment to fix it. This seamless integration of physical and digital can significantly reduce visits and parts used while granting the customer peace of mind.

Organisations often access new technologies or ideas by acquiring start-ups and then integrating them. This approach risks killing the start-up's culture and chasing away the talent acquired during its creation. Smart companies prefer to build hybrid relationships with start-ups strong enough to learn and find synergies but weak enough to avoid destroying the culture. So even though they may own the start-ups, they allow them to operate as semi-independent businesses.

MYTH	REALITY
Digital is about technology.	**It's about the customer.**

The credit card giant Mastercard has a systematic process for engaging employees from various functional areas can submit ideas to qualify for three stage awards: Orange Box, Red Box, and Green Box. The Orange Box gives employees a chance to explore their ideas and pitch them and receive a reward for $1,000 and coaching to develop a presentation about solving a specific customer problem. The Red Box stage turns an idea into a concept, the team receives $25,000 for testing, prototype development, and research and a 90-day guide outlining the steps needed to refine the concept. The Green Box is to create a commercialised product from an official incubation project. At this stage team members leave their jobs for six months to work on the project.

Digital transformation may require radically altering back-end legacy systems, but starting with a sweeping IT overhaul comes with great risks. Smart companies find a way to quickly develop front-end applications while slowly replacing their legacy systems in a modular, agile fashion. Experience suggests that attempts to replace multiple complex, mission-critical systems all at once nearly always end in disaster. Rather than embark on a complete overhaul, it is better to develop a plan to replace current technology, working with bespoke solutions to focus on a better customer experience and to learn from customers what they wanted in a digital world.

For most companies, even those truly threatened by disruption, digital transformation is not usually about a root-and-branch reimagining of the value proposition or the business model. Rather, it is about both transforming the core using digital tools and discovering and capturing new opportunities enabled by digital. The keys to success have been a focus on customer needs, organizational flexibility, respect for incremental change, and awareness that new skills and technology must be not only acquired but also protected - something the best companies have always been good at.

6. World Economic Forum Future Scenarios

"The goal in using scenarios is to reveal the dynamics of change and use these insights to reach sustainable solutions to the challenges at hand. Scenarios help stakeholders break through communication barriers and see how current and alternative development paths might affect the future. The ability to illuminate issues and break impasses makes them extremely effective in opening new horizons, strengthening leadership, and enabling strategic decisions."

The Organisation for Economic Co-operation and Development (OECD)

The World Economic Forum (WEF)'s Shaping the Future of Construction initiative, developed 3 possible scenarios of how the global social and economic context could look like in the future and explored the implications on the infrastructure and construction industry. These are shown in Figure 1.

Figure 1: Potential scenarios impacting the industry (Source: Future of Construction, World Economic Forum)

The scenarios of how the industry could look in the future are based on global trends. These scenarios clearly show that existing capabilities, business models and strategies will not be sufficient to succeed. The WEF report encourages urgent actions that are relevant in any possible future:

1. **Attract new talent and build up required skills**– as any future scenario requires talent with substantially different skills than today's workforce possesses, and adequate upskilling processes are largely not in place.

2. **Integrate and collaborate across the construction industry's value chain**– as the construction industry is characterized by a disintegrated and highly fragmented value chain, which hampers the seamless data flows and integrated systems that are essential in any future scenario.

3. **Adopt advanced technologies at scale**– as the construction industry has been slow to adopt new technologies and still heavily relies on manual labour and mechanical technologies, resulting in poor productivity.

4. **Maximize the use of data and digital models throughout processes** – to review existing practices and infrastructure asset portfolios and embrace new business opportunities; and to enable change-management and adaptiveness.

The myriad potential changes in the industry leads to high ambiguity and makes it impossible to predict the future. However, with scenario planning, involved stakeholders can prepare for a variety of possible futures. This first Report will focus on the digitalisation of construction. Over the past decade, digital technologies have transformed whole industries, ushering in the Fourth Industrial Revolution. New technologies do not just satisfy consumer demands for better products and services. In most industries, innovations improved companies' productivity and sustainability and reshaped the skills and competencies needed to thrive.

However, during the same period, the construction industry has continued operating as it has for the past 50 years, with a heavy reliance on manual labour, mechanical technology and established operating and business models resulting in productivity stagnation.

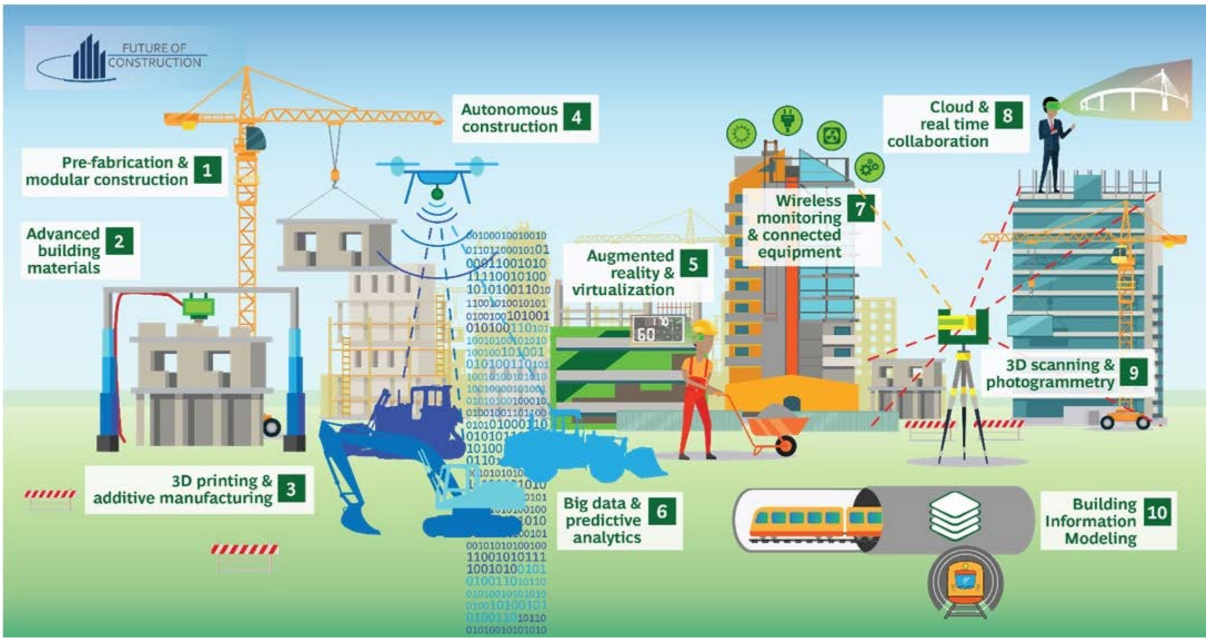


Figure 2: Top 10 disruptive technologies in infrastructure and construction (Image: Future of Construction, World Economic Forum, Boston Consulting Group)

Digital technologies are slowly starting to enter the construction industry, changing how built assets are designed, constructed, and maintained. Those technologies (Figure 2) including building information modeling (BIM), prefabrication, automated and robotic equipment, and 3D-printing, are starting to make both economic and social impact on the industry. The WEF estimates that full-scale digitisation could help the industry generate between $1 trillion and $1.7 trillion in annual cost savings through productivity gain in the next decade. Global megatrends such as rapid urbanisation, climate change, resource depletion, and the widening talent gap are some of the most pressing trends that should motivate businesses to rethink their practices.

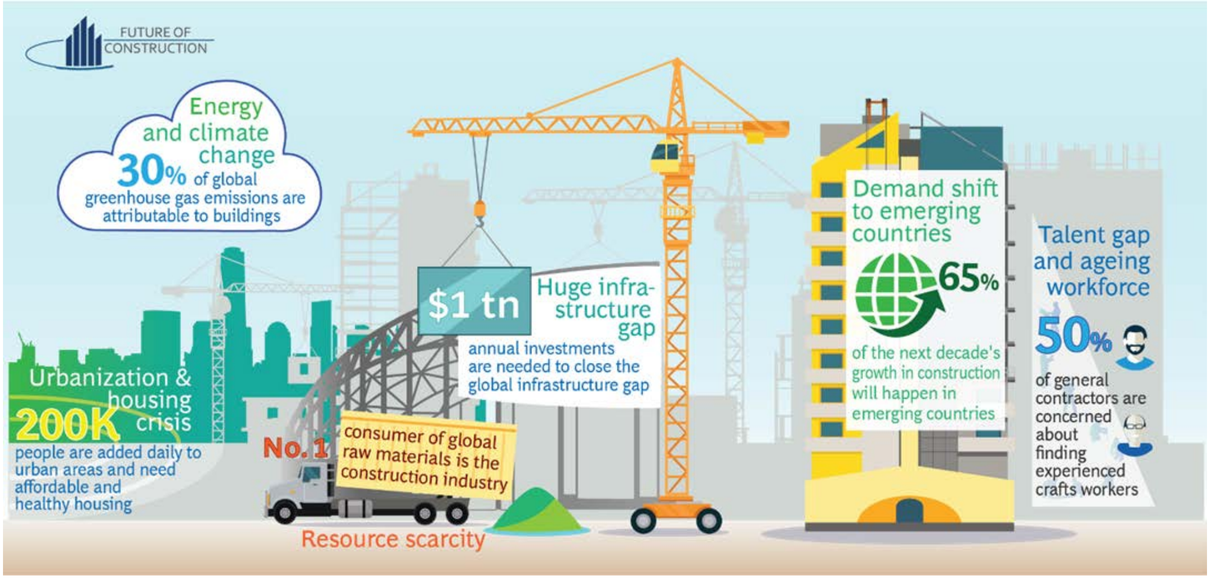


Figure 3: Megatrends create imperative for change in the sector (Image: Future of Construction, World Economic Forum, Boston Consulting Group)

The report states that 74% of the industry's CEOs who attended the 2018 annual meeting of the World Economic Forum in Davos reported that they considered attracting new talent and improving the skills of the existing workforce to be among the top three actions for keeping pace with upcoming disruptions. The other two priorities they named were improving integration and collaboration along the value chain (65%) and adopting advanced technologies at scale (61%).

The scenarios depict three extreme yet plausible versions of the future. In *Building in a virtual world*, virtual reality touches all aspects of life, and intelligent systems and robots run the construction industry. In *Factories run the world*, a corporate-dominated society uses prefabrication and modularization to create cost-efficient structures. In *A green reboot*, a world addressing scarce natural resources and climate change rebuilds using eco-friendly construction methods and sustainable materials. It is important to keep in mind that the scenarios are not predictions of the future. Rather, they demonstrate a broad spectrum of possible futures. In the real future, the construction industry will most probably include elements of all three.

Creating scenarios helps decision-makers understand the differing ways present trends can play out in the future. Industry decision-makers should use scenarios and recommendations based on corresponding transformation imperatives as a foundation from which to create strategies to prepare for the future. As time passes and the direction of future developments becomes clearer, decision-makers can fine-tune their plans accordingly.

7. Research Methodology

Having considered the previous sections which provided the context and a four step approach for the effective implementation of digital transformation, this section introduces the methodology adopted for this report which utilises scenarios proposed by the World Economic Forum (WEF) that depict three extreme yet plausible versions of the future. Although the themes identified for this report can be argued to have some influence on all potential scenarios, the research team have categorised them into the most relevant scenario.

In addition to grouping the ten identified themes using the three WEF Future Scenarios, Table 1 below provides an indication of the impact that each theme has on digital transformation in the next 5, 10 and 20 years based on the literature and expert interviews. Furthermore, each theme has a provisional assessment of its position in the innovation portfolio/pipeline for a construction organisation. The impact on digital transformation for each theme is assessed either High (H), Medium (M) or Low (L).

Table 1: Analysis of the key themes (Timeline, Innovation Portfolio position and impact on digital transformation)

Theme	VIRTUAL			FACTORY			GREEN			Innovation Portfolio
	5	10	20	5	10	20	5	10	20	
1. Connected workflows	H	H	H							Core
2. Artificial Intelligence/Machine Learning	M	H	H							Adjacent
3. Wearable & Site Optimization Technologies	M	M	H							Adjacent
4. Augmented/Virtual/Mixed Realities	L	M	H							Adjacent
5. Robotics and Automation				L	M	H				Adjacent
6. Industrial Construction/Platforms & DFMA				M	H	H				Adjacent
7. 3D/4D Printing				L	M	H				Transform
8. Biotechnology & Advanced Materials				L	M	H				Transform
9. Sustainable Design & Climate Change							H	H	H	Core
10. Smart Cities & National Digital Twin							L	M	H	Adjacent

By using the proposed Four Step approach as the foundation for effective digital transformation, the opportunities that are proposed in the following sections will stand a much better chance of success.

Each of the ten identified themes is introduced with a table that provides a summary of the key trends of theme, along with an indicative timeline of its application and its potential impact to a construction organisation or its customers.

8. Future Scenario A: Building in a Virtual World

Theme 1: Connected workflows
Theme 2: Artificial Intelligence/Machine Learning
Theme 3: Wearable & Site Optimization Technologies
Theme 4: Augmented Reality

8.1 Theme 1: Connected workflows

Key Trends	Timeline	Impact
Key Trend 1: Big Data - increase in the use of Building Information Modelling (BIM) and other technologies has generated large amounts of both structured (clearly defined data types whose pattern makes them easily searchable) and unstructured (data that is usually not as easily searchable, including formats like audio & video) data. The goal is to fully utilise this data by employing Machine Learning algorithms to provide predictive analytics to help us make better decisions in real time. By looking for patterns across projects, early signs of problems in the supply chain and the opportunity to optimise cashflow and schedule overruns could be achieved. **Data from Machine Learning algorithms are used to predict behaviour (both project team & stakeholders), assess performance, improve market competitiveness and allocate resources.**	**Now (0-5 yrs)**	**High**
Key Trend 2: Internet of Things (IoT) objects can be people, animals, vehicles, plant, appliances and building components. The allocation of an IP address to these objects means that they have the potential to communicate with other objects on the network. Internet-enabled devices are influencing the development of manufacturing processes, communications technologies, energy distribution, transport networks, healthcare and so on. The high number of components used in the construction and operation of buildings means that the potential for IoT application is very significant in the areas of self-diagnosis, self-configuration and self-optimisation. **This can be achieved through a network of embedded sensors, meters, appliances and devices capable of sending and receiving data about changes to their current physical state and surrounding environment over the internet.**	**Now (0-5 yrs)**	**High**
Key Trend 3: Blockchain is a simple database with special properties of information, such as transactions or agreements that are stored across a network of computers. That information is stored chronologically, viewed by a community of users, but is decentralised and is not usually managed by a central authority such as a bank or a government. Once published, the information on the blockchain cannot be changed. It has the potential to facilitate a paradigm shift in the industry towards effectiveness, accountability and transparency, improve efficiency and digital workflows by shifting current payment and project management systems towards a more transparent and fair practice. One notable application is the reduction of late payments, remediation and disputes, SMEs are no longer placed in continuous cash flow risk. Instead, the industry as a whole can become a more trusted entity. Through smart contracts, business processes and administrative tasks can be automated to increase efficiency and always be aligned with the agreed contractual terms. This can result in significant cost savings, increment in the low margins of the industry, and better control project costs. **Good examples of potential application include releasing offsite payments, managing house purchase contracts, and assuring sub-contractor payments.**	**Next (5-10 yrs)**	**High**

Connected workflow possibilities

Autodesk's *Constructing with the Power of Digital* report provides a useful vision for the future of the construction industry in the era of connection. It focuses on three technology-driven disruptions – In how we design, build and operate buildings and infrastructure – which are giving rise to a new era for the construction industry. They propose a new set of connected capabilities:

• *Connected Teams* the capability to connect people together dynamically, across geographies and commercial boundaries in real-time. This will replace the industry's traditional, asymmetric approach to collaboration; and will reduce the overheads of having to access talent and expand the pool of available talent by the use of work-exchange hubs and crowdsourcing platforms

• *Connected Insights* the capability to solve highly complex design problems, by connecting infinite computing power in the cloud, with big data and smart algorithms to make the best possible design decisions for everything from buildings to commercial strategies

• *Connected Outcomes* the capability to 'start with the end in mind' by connecting the digital and physical worlds together seamlessly, through reality capture, gaming engines and augmented/virtual reality. This will enable project teams to explore and refine options in the context of the real-world systems in which they are planned to reside – physical, environmental, economic, social

• *Connected Delivery* the capability to go from a design for a building or infrastructure asset in a silicon environment into a finished real-world asset with the minimum number of physical 'touches', waste, cost and supply-chain overheads, through the use of digital fabrication, digitally-driven prefabrication, and micro-factories

• *Connected Assets* the capability to connect real-world physical buildings and infrastructure assets digitally, to understand every aspect of how those assets perform, are utilised and interact with the systems in which they reside. This collected data can then be used to inform future work pipelines

• *Connected Capital* the capability to connect project proposals rapidly with committed funding by mitigating construction risks through highly digitally driven project delivery, and data-driven insights into the performance of proposed assets across their lifecycle; and connect project proposals with new sources of capital, through crowdfunding, and digital assessments of 'remaining value' in existing built assets.

8.1.1 Big Data

According to BSRIA, *Big Data* refers to data sets that are so large or complex that traditional data processing software is inadequate to deal with them. Big data is measured in terabytes, petabytes and even zettabytes (1 trillion gigabytes). As computational power and data storage capabilities have increased, and the cost of sensors has dropped, so the amount of data we are able to gather, create and process has risen very significantly. In 2015, IBM suggested that every day, we create 2.5 quintillion bytes of data, and that 90% of the data in the world has been created in the last two years. Using a very loose description of 'data' they suggest that this includes, data from sensors, posts to social media sites, pictures, videos, purchase transaction records, GPS signals and so on. This proliferation of high-volume data is described as 'big data'. In buildings, data might be generated by a very wide variety of sources, including:

- Design and construction (for example building information modelling)
- Post occupancy evaluation
- Utilities, building services, meters, building management systems
- Infrastructure and transport systems
- Market analysis and bidding

The increase in the use of Building Information Modelling (BIM) and other technology tools has generated large amounts of both structured (clearly defined data types whose pattern makes them easily searchable) and unstructured (data that is usually not as easily searchable, including formats like audio & video) data. The goal is to fully utilise this data by employing Machine Learning algorithms to provide predictive analytics to help us make better decisions in real time. By looking for patterns across projects, early signs of problems in the supply chain and the opportunity to optimise cashflow and schedule overruns could be achieved. Data from these sources can be used to understand behaviour (both project team & stakeholders), assess performance, improve market competitiveness, allocate resources and so on. However, historically, it has been difficult and expensive to collect this data, and its variety of quality, structure and format made it difficult to use, sometimes for example requiring the manual transfer of data from paper records into digital systems. This meant that data applications tended to be restricted to specific technical functions, rather than being used for high-level decision making.

8.1.2 Internet of Things (IoT)

The Internet of Things (IoT) refers to the application of unique identifiers to physical objects that enables them to be connected to a network allowing the transfer of data to and from those objects. IoT objects can be people, animals, vehicles, plant, appliances, building components and so on. The allocation of an IP address to these objects means that they have the potential to communicate with other objects on the network. Such objects are sometimes described as 'smart' objects, for example, a smart meter, smart phone and so on. Internet-enabled devices are influencing the development of manufacturing processes, communications technologies, energy distribution, transport networks, healthcare and so on. The high number of components used in the construction and operation of buildings means that the potential for IoT application is very significant.

Self-diagnosis, self-configuration and self-optimisation. In simple terms, IoT is a network of embedded sensors, meters, appliances and devices capable of sending and receiving data about changes to their current physical state and surrounding environment over the internet. The sensors that have been put in everyday items such as mobile phones have now reached the construction industry. The various objects, equipment and components used in the sector can have telematics sensors installed to monitor operating conditions. The conditions can then be tracked remotely and reported back through specialist software. IoT makes the running of a building a data-driven process. The technology can pull data from sensors to help facilities managers form useful operational insights. Currently, many existing building management systems (BMS) do not fully utilise the vast amount of operating data being generated. IoT can help identify operational issues more easily as most building operators do not have the time to analyse historical trend data in order to identify these operational problems. Having a BMS that can integrate and automate data analysis that results in simple and actionable insight that will allow building owners to optimise energy usage and make cost savings. There are examples of systems manufacturers looking to create smart BMS systems i.e. that respond using machine learning and sensors to automate building management. *This topic along with Blockchain will be explored further in the Facilities Management paper*.

8.1.3 Blockchain

A Blockchain is a distributed ledger (a simple database with special properties) of information, such as transactions or agreements that are stored across a network of computers. That information is stored chronologically, can be viewed by a community of users, but is decentralised and is not usually managed by a central authority such as a bank or a government. Once published, the information on the blockchain cannot be changed. As an example, just imagine a system where instead of having one central accounting book of all transactions between contracting parties, and there is a system maintaining multiple records simultaneously by every party. There is, in its place, just one single source of information or single source of truth (immutable records of transactions, interactions) on the blockchain maintained by the network and its protocol – copied and shared with all parties who interact on the network[6]. Blockchain was first widely introduced almost 10 years ago as the underlying technology of Bitcoin. It has the potential to facilitate a paradigm shift in the industry towards effectiveness, accountability and transparency. Blockchain technology has the potential to improve efficiency and digital workflows by shifting current payment and project management systems towards a more transparent and fair practice. By reducing late payments, remediations and disputes, with the potential to reduce cash flow risk to SMEs. Instead, the industry as a whole can become a more trusted entity. Through smart contracts, business processes and administrative tasks can be automated to increase efficiency and always be aligned with the agreed contractual terms. This can result in significant cost savings, helping with the low margins of the industry, and better control project costs. Good examples of potential application include releasing offsite payments, managing house purchase contracts, and assuring sub-contractor payments.

[6] Penzes (2018) Blockchain Technology in the Construction Industry, ICE

8.2 Theme 2: Artificial Intelligence/Machine Learning

Key Trends	Timeline	Impact
Key Trend 1: Artificial Intelligence is the broader concept of machines being able to carry out tasks in a way that we would consider "smart". Artificial Intelligences – devices designed to act intelligently – are often classified into applied or general. Applied AI is most common – systems designed to intelligently trade stocks and shares, or manoeuvre an autonomous vehicle would fall into this category. Generalized AIs – systems or devices which can in theory handle any task – are less common, but this is where some of the most exciting advancements are happening today. It is also the area that has led to the development of Machine Learning.	**Now (0-5 years)**	**High**
Key Trend 2: Machine Learning is a current application of AI based around the idea that we should really just be able to give machines access to data and let them learn for themselves. The realisation that rather than teaching computers everything they need to know about the world and how to carry out tasks, it might be possible to teach them to learn for themselves. The development of neural networks has been key to teaching computers to think and understand the world in the way we do, while retaining the innate advantages they hold over us such as speed, accuracy and lack of bias. A Neural Network is a computer system designed to work by classifying information in the same way a human brain does. It can be taught to recognise, for example, images, and classify them according to elements they contain. Autodesk IQ is an example of Neural Network and an example of Machine Learning. Which provides opportunities to harness the way we automate the collection and analysis of real-time data to provide the project team the ability to make informed decision that will maximise project success.	**Now (0-5 years)**	**High**
Key Trend 3: Generative Design is a framework for combining digital computation and human creativity to achieve results that would not otherwise be possible. It involves the integration of a rule-based geometric system, a series of measurable goals, and a system for automatically generating, evaluating, and evolving a very large number of design options. This approach offers many benefits for designing buildings and cities – including managing complexity, optimizing for specific criteria, incorporating a large amount of input from past projects and current requests, offering transparency about project assumptions, and offering a "live model" for post-occupancy adaptation. The framework consists of three main components: 1. generate a wide design space of possible solutions through a bespoke geometry system; 2. evaluate each solution through measurable goals; 3. evolve generations of designs through evolutionary computation. **Case 1: Alkmaar Residential Neighbourhood, Van Wijnen**	**Now (0-5 years)**	**High**

8.2.1 Artificial Intelligence

Artificial Intelligence is the broader concept of machines being able to carry out tasks in a way that we would consider “smart”. Artificial Intelligence is often classified into one of two fundamental groups – applied or general. Applied AI is far more common – systems designed to intelligently manoeuvre an autonomous vehicle would fall into this category. Generalised AI – systems which can in theory handle any task – are less common, but this is where some of the most exciting advancements are happening today. It is also the area that has led to the development of Machine Learning. Often referred to as a subset of AI, it’s really more accurate to think of it as the current state-of-the-art.

Machine Learning is a current application of AI based around the idea that we should really just be able to give machines access to data and let them learn for themselves. Two important breakthroughs led to the emergence of Machine Learning as the vehicle which is driving AI development forward with the speed it currently has. One of these was the realisation that rather than teaching computers everything they need to know about the world and how to carry out tasks, it might be possible to teach them to learn for themselves. The second, more recently, was the emergence of the internet, and the huge increase in the amount of digital information being generated, stored, and made available for analysis. The development of neural networks has been key to teaching computers to think and understand the world in the way we do, while retaining the innate advantages they hold over us such as speed, accuracy and lack of bias. A Neural Network is a computer system designed to work by classifying information in the same way a human brain does. It can be taught to recognise, for example, images, and classify them according to elements they contain. Autodesk IQ is an example of Neural Network. Which provides opportunities to harness the way we automate the collection and analysis of real-time data to provide the project team the ability to make informed decision that will maximise project success. An example may be the classification of "high risk" issues which could potentially identify a project or subcontractor as high risk based on the number of associated high-risk issues that are flagged up by the Machine Learning capabilities. The project team can use Construction IQ as an assistant to help manage risk in conjunction to support their decision making

8.2.2 Autodesk Construction IQ

Construction IQ takes data from BIM 360 Field Management and Account Admin modules to transform that data into simple and actionable insights through the application of analytical techniques and machine learning.

There are two broad categories of Construction IQ user, each with different associated permissions and workflows:

Executive (Director of Quality, VP of Operations): Can see an executive overview of all projects in the account, which provides visibility of project and subcontractor risk and identifies cross-project patterns.

Project Lead (Superintendent, Project Manager): Can see a project overview, including the risk level for all subcontractors and issues in the project.

The daily risk assessment feature uses algorithms to sort through hundreds or thousands of project issues, and to categorise and prioritise the highest risk projects, subcontractors, and issues that need attention each day. This will be based on existing data collected which may be sitting in separate databases which can now be entered into Construction IQ for analysis. An issue is classified as "high risk" if it involves the risk of a fall, a water hazard, or a pending safety inspection; or if it's overdue. Indicating a project or subcontractor as high risk is a suggestion based on the number of associated high-risk issues.

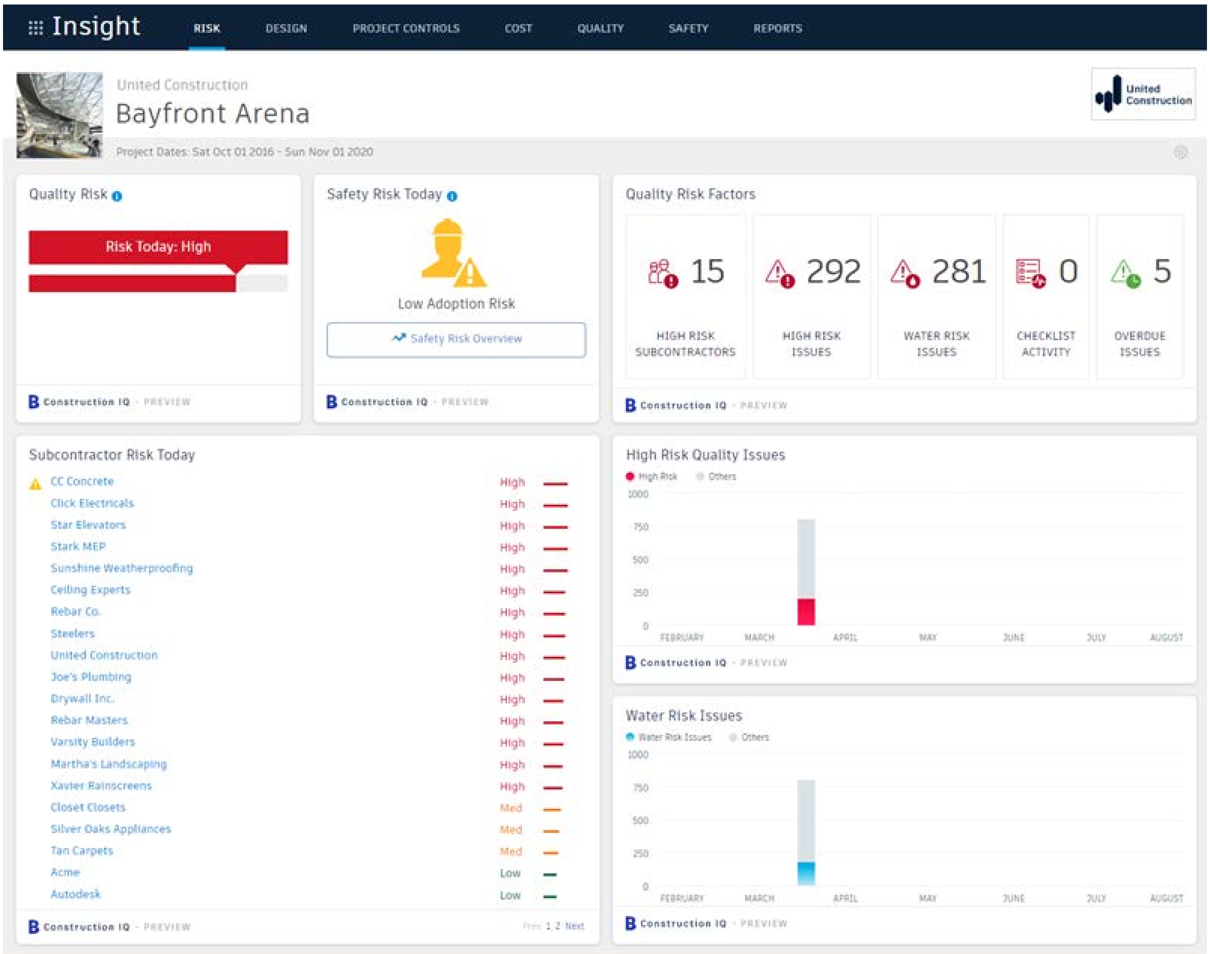


Figure 4: Autodesk Construction IQ (Source: Autodesk)

"With Construction IQ and many of the partners Autodesk works with, we're starting to see some really nice ways to get predictive insights from the data. So it's still about giving you recommendations or insights and that's where we are today.

The next level is how do we make it more of a workflow automation step? So it's not just about providing recommendations but is about assisting you with automating some of your key workflows and filling some gaps."

- **Manu Venugopal**, Senior Product Manager, AI and Machine Learning in Construction, Autodesk

8.2.3 Generative Urban Design: Autodesk Research and Van Wijnen

Autodesk Research's in-house architectural studio, The Living, is a pioneer in the application of generative design technology. In late 2016, The Living was approached by Van Wijnen, an innovative Dutch construction company interested in reinventing the way the firm built homes. Van Wijnen wanted to apply generative design at the urban scale, exploring possibilities around the layout of residential areas based on financial, sociological, or environmental metrics. Generative design is a framework for combining digital computation and human creativity to achieve results that would not otherwise be possible. It involves the integration of a rule-based geometric system, a series of measurable goals, and a system for automatically generating, evaluating, and evolving a very large number of design options.

This approach offers many benefits for designing buildings and cities – including managing complexity, optimizing for specific criteria, incorporating a large amount of input from past projects and current requests, navigating trade-offs based on real data, structuring discussion among stake-holders about design features and project objectives, offering transparency about project assumptions, and offering a "live model" for post-occupancy adaptation. The framework consists of three main components: 1. generate a wide design space of possible solutions through a bespoke geometry system; 2. evaluate each solution through measurable goals; 3. evolve generations of designs through evolutionary computation.

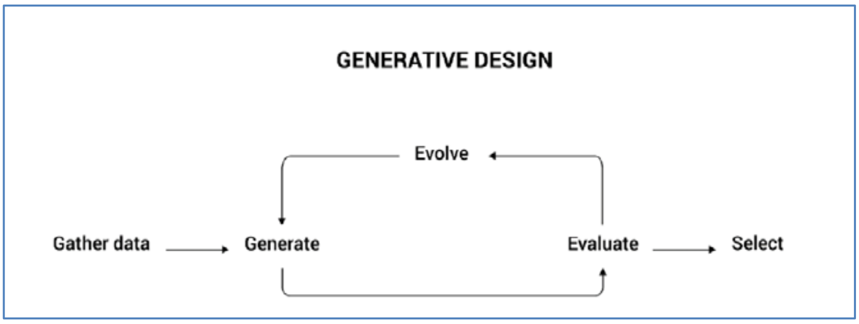
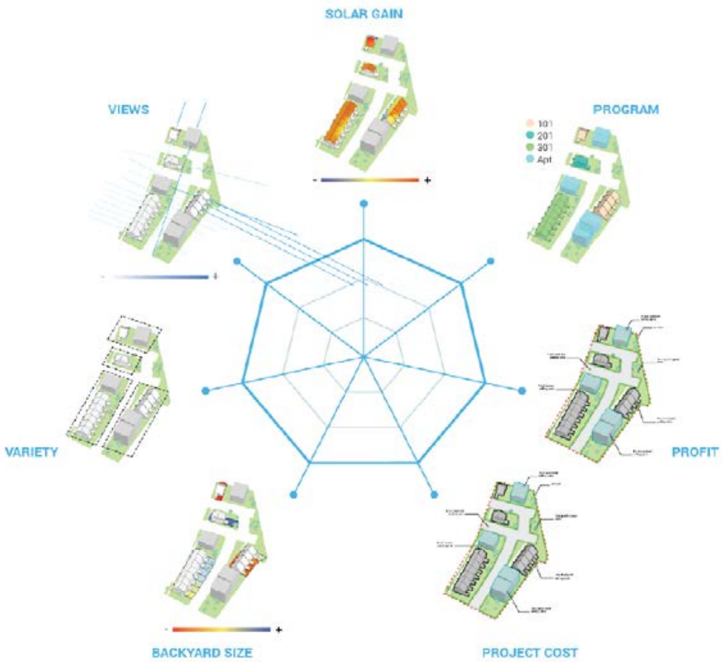


Figure 5: The generative design workflow (*Source*: Autodesk University).

8.2.4 Case 1: Alkmaar Residential Neighbourhood, Van Wijnen

Van Wijnen is an innovative Dutch development and construction company that seeks to change the way buildings are designed and made. In 2017 they partnered with The Living to apply generative design at the scale of the city. The project involved the design of a geometric model that could meet the local building code constraints (such as number and location of access streets, setbacks, parking rules etc.), and satisfy the developer's requirements (such as amount of two-story residential units and apartment buildings). Urban design problems generally present many stakeholders, often representing conflicting requirements and interests, thus intensifying the complexity of the design. Generative design is able to aid the management and structuring of such complexity through the definition of the goals. In this case the project involved seven distinct goals, including financial ones (revenue and construction cost), environmental ones (such as solar gain and views), as well as more architectural ones (such as variety). Generative design has helped Van Wijnen improve their planning process for residential neighbourhoods. They have use this technology as part of their digital strategy to build a robotically operated prefabrication factory that can further streamline the process from design to build.



For urban design problems, the generative design framework can aid the management and structuring of complexity through the definition of goals that can represent the interest of different stakeholders.

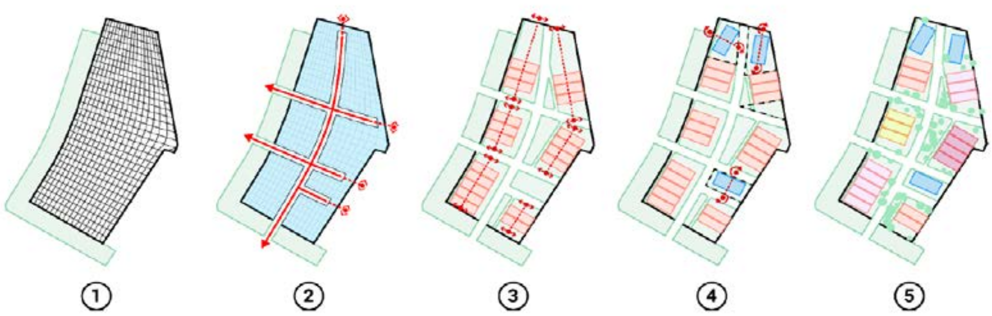


Figure 6: Geometric system: (1) create mesh from boundary; (2) generate streets; (3) subdivide into lots; (4) place housing units; (5) place apartment buildings (*Source*: Autodesk University).

8.3 Theme 3: Wearable & Site Optimisation Technologies

Key Trends	Timeline	Impact
Key Trend 1: Inertial Measurement Units (IMU) sensor technology can be used as a wearable sensor-based real-time motion-warning personal protective equipment (PPE) to automatically assess ergonomically unsafe postures. **Case 1**	**Now (0-5 years)**	**High**
Key Trend 2: Process monitoring and control - Process monitoring and control provides the basis for tracking and measurements required for activity analysis. It uses automated data collection process to track resources and measure the progress of work. This can streamline workers' activity analysis more efficiently compared to the conventional (manual) approaches such as direct observations and survey-based methods which are tedious, time consuming, and error-prone. **Case 2**	**Now (0-5 years)**	**High**
Key Trend 3: Wireless and wearable electroencephalography (EEG) Construction workers can become insensitive to hazards around jobsite because of their long-term exposure to risks. Therefore, to successfully achieve high levels of safety management practices, maintaining construction workers' vigilance and monitoring their attention levels is important. The technology uses a wireless and wearable electroencephalography (EEG) system to quantitatively and automatically assess construction workers' perceived attention/vigilance levels compared with the actual work environment risks towards identifying mismatches **Case 3**	**Next (5-10 years)**	**Med**
Key Trend 4: Exosuits or Exoskeletons are metal frameworks fitted with motorized muscles to multiply the wearer's strength. The robotic suits' metal framework somewhat mirrors the wearer's internal skeletal structure. The suit makes lifted objects feel much lighter, and sometimes even weightless, reducing injuries and improving compliance. The exosuits, or exoskeletons used within the construction industry are ripe for growth. **Case 4**	**Next (5-10 years)**	**High**

Wearable & Site Optimisation Technologies

Automated technologies for data acquisition in construction domain applications including vision-based techniques and wireless sensor-based methodologies have been proposed and investigated by a number of researchers for automated activity analysis. The use and implementation of innovative techniques such as persuasive technology which has the potential to improve efficiency, productivity and occupational health and safety in the construction industry is becoming popular with some major contractors. Averting construction site injuries and deaths with emphasis solely on "human to human" interaction has not yielded optimum results. Hence, the adoption of deep learning which is an artificial intelligence function that imitates the workings of the human brain in processing data and creating patterns for use in decision making and persuasive technology are now being used to deter unsafe acts of workers and improve the overall health and safety performance within the industry. To mitigate construction site accidents and hazards, it is considered that an intelligent construction site should have the capability of tagging, tracking and locating resources such as labour, materials and equipment in real-time. Deep learning and object detection models could therefore provide context for unsafe detection and persuasive technology enables real-time communication with workers.

Studies conducted in assessing the sedentary lifestyle of office workers indicated that the best possible approach to deter workers from such lifestyle was by using persuasive technology. The adoption of persuasive technology has the potential to persuade and change human behaviour and the impact of incorporating motivational strategies is fundamental in the design of systems aimed at human behavioural change[7]. Therefore, with a framework for every change in human behaviour, constant non-coercive reminders or motivation are essential towards achieving such goals. Wearable technologies give more control to the user by focusing on the prevention and helping people to manage their behaviour.

8.3.1 Case 1 – Wearable Inertial Measurement Units (WIMU)-based motion warning system

The wearable sensor-based real-time motion warning enables workers to be self-aware and self-manage ergonomically hazardous work positions during operations e.g. non-neutral trunk postures like stooping, squatting and kneeling for long working hours. The aim is to prevent or minimise the risk of lower back injuries or musculoskeletal disorders (MSDs). The wearable sensor which can be connected to a smartphone application sends any dangerous motion assessment using an alarm system to gently prompt the worker of their real-time hazardous operational postures but without interfering in the worker's normal task functions. The essence of the developed smartphone application is to receive and process motion data captured by WIMU sensors via Bluetooth technology. The real-time sensor output is transferred to the smartphone application for data processing and all operational motion posture data received and processed are transferred to the database in the backend server through site Wi-Fi. The processed data can be used by safety managers to accurately assess individual ergonomic hazard levels within the site and this is also useful for evaluating on-site safety management and scheduling relevant ergonomic training. The system may help construction workers better understand the ergonomic hazard level of their actions based on the frequency of individual alarms. Research into ergonomic hazard assessment suggest that both vision-based methods (e.g. Kinect and Stereo Camera System) and wearable sensor systems (e.g. joint angle measurement systems and IMUs) are effective on-site ergonomic assessment tools.

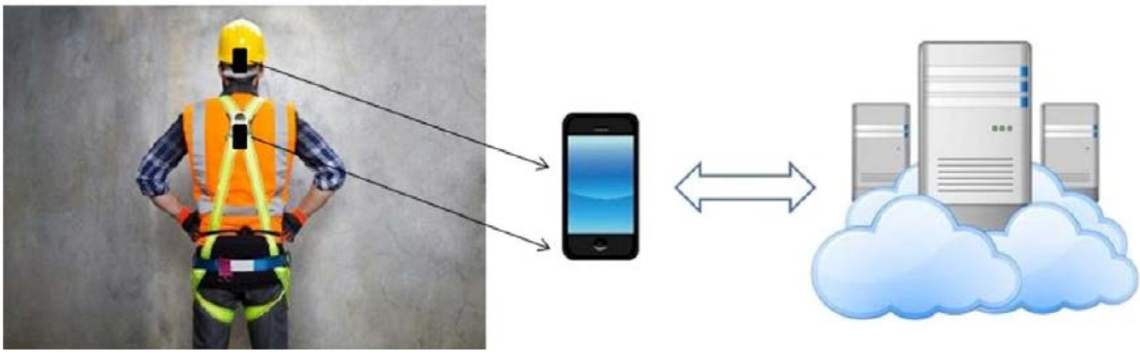


Figure 7: The WIMU-based real-time motion warning system framework[8].

[7] Ferraro, Venere et al. (2017) Persuasive Technology as key to increase Working Health Condition. The Case study of a Wearable System to prevent Respiratory Disease. The Design Journal.

[8] Xuzhong Yan; Heng Li; Angus R. Li; Hong Zhang; - Wearable IMU-based real-time motion warning system for construction workers' musculoskeletal disorders prevention; Automation in Construction 74 (2017) 2–11; http://dx.doi.org/10.1016/j.autcon.2016.11.007

8.3.2 Case 2 – Activity Analysis through process monitoring and control

Process monitoring and control provides the basis for tracking and measurements required for activity analysis. It uses automated data collection process to track resources and measure the progress of work. This can streamline workers' activity analysis more efficiently compared to the conventional (manual) approaches such as direct observations and survey-based methods which are tedious, time consuming, and error-prone. The two main techniques currently used for process monitoring are vision-based and wireless sensor-based techniques. Vision-based activity recognition is based on the use of visual sensing facilities, such as video cameras, to monitor workers' behaviour and environmental changes. Vision-based methods are often prone to existing obstructions and illumination variability in construction jobsites. The wireless sensor-based methodologies collect spatiotemporal activity data i.e. modelling users' activities at different locations and time from user behavioural data and with the ability to predict future behavioural responses. It does not require a clear line-of-sight (LOS) and extensive computations and it provides a relatively low cost solution. The process monitoring and control can provide effective and timely analysis and tracking of workforce activities that are essential to overall productivity measurement, progress evaluation, labour training programs, safety and health management[9][10].

8.3.3 Case 3 - Monitoring workers' attention and vigilance in construction activities

Construction workers can become insensitive to hazards on site because of their long-term exposure to risks. Therefore, to successfully achieve high levels of safety management practices, maintaining construction workers' vigilance and monitoring their attention levels is important. The use of a wireless and wearable electroencephalography (EEG) system to quantitatively and automatically assess construction workers' perceived attention/vigilance levels compared with the actual work environment risks could help to identify mismatches. The worker's perceived risk level can be impeded by both external and internal factors. The external factors are related to the work environment, such as construction site environment, exposure level, work group and warning signs, while the internal factors are related to individual conditions, such as experience, working memory, and work-related stress. The internal factors are considered as the major reasons why construction workers ignore warning signals and incorrectly assess potential risks. Among those internal factors, working memory is thought to be the most difficult factor to quantify and the major cause of accidents during the execution of construction tasks. Working memory or mental workload refers to the amount of human mental resources required to efficiently perform tasks and perceive hazards. When a worker experiences decay of working memory, they potentially fail to detect risk stimuli in the surrounding environment or underestimate the associated risks, resulting in adopting unsafe behaviours. The electroencephalography (EEG) signals collect data from a wearable EEG monitoring device preinstalled in a helmet to measure construction site workers' vigilance/attention level with regard to surrounding hazards and for detecting mismatches between the perceived risks and physical risks. The EEG sensors monitor the electric field intensity of the brain region; with the power of different EEG channels directly reflecting the various brain activities. Investigators can measure the level of knowledge a construction worker has commanded in recognising site hazards and identify the discrepancy between the perceived risk and the factual risk in order to develop tailor-made programs and interventions to minimise site accidents. The results could help to improve field monitoring, safety management, and training programs[11].

[9] L. Chen, J. Hoey, C.D. Nugent, D.J. Cook, Z. Yu, Sensor-based activity recognition, IEEE Trans. Syst. Man Cybern. Part C 42 (6) (2012) 790–808, http://dx.doi.org/10.1109/tsmcc.2012.2198883

[10] Reza Akhavian, Amir H. Behzadanb, 2016; Smartphone-based construction workers' activity recognition and classification, Automation in Construction 71 (2016) 198–209; http://dx.doi.org/10.1016/j.autcon.2016.08.015

[11] Di Wang, Jiayu Chen, Dong Zhao, Fei Dai, Changjian Zheng, Xiaobing Wu; Monitoring workers' attention and vigilance in construction activities through a wireless and wearable electroencephalography system; Automation in Construction 82 (2017) 122–137; http://dx.doi.org/10.1016/j.autcon.2017.02.001

8.3.4 Case 4 - Exoskeletons for Construction Workers

For construction workers of the not-so-distant future, the term “suit up” may refer to putting on a metal exosuit, an exoskeleton for construction workers which provides robotic strength. Exosuits or exoskeletons are metal frameworks fitted with motorized muscles to multiply the wearer’s strength. The robotic suits’ metal framework mirrors the wearer’s internal skeletal structure, making lifted objects feel much lighter, and sometimes even weightless, reducing injuries and improving compliance. Exosuits used within the construction industry are ripe for growth. ABI Research predicts the robotic exoskeleton market alone will reach $1.8 billion in 2025, up from $68 million in 2014. While a number of companies make exosuits for construction and manufacturing use, they have made limited headway as of yet in the construction field and few, if any, construction companies have adopted them due to cost issues. The construction industry will be taking to these wearable powered or unpowered robotic exosuits in great numbers as prices reduce. One reason the robotic suits are ripe for adoption by builders is their falling prices, e.g. two types of suits, the **Chairless Chair**[12] and the **EksoWorks Vest**[13], sell for about $5,000 each, far less than the type of full-body suits that help those who are paralyzed walk. Exosuits can be either passive— that is, without the use of actuators (a device that converts energy, usually electrical, into physical motion) to help with lifting or hauling—or active, which use actuators to aid in these activities. Within the construction and manufacturing industries, passive systems are popular, as these suits are less expensive and actuators are not necessary to relieve the exoskeleton user of a payload or bodyweight. Examples in construction the Mounted Arm Support Limb for tool-holding and the Back Support Exosuit.

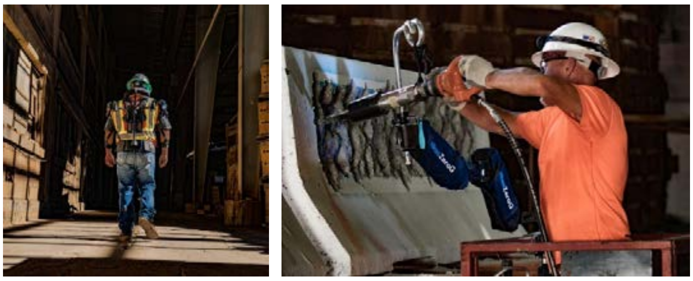


Figure 8: Back Support Exosuit & Arm Support Limb (Source: https://eksobionics.com/eksoworks/ **)**

Interest in wearable and site optimisation technologies has increased significantly as a result of the Covid-19 pandemic. The importance of maintaining social distancing and the need for contact tracing has come to the fore with most sites putting in place social-distancing protocols. Existing technology providers and solutions have been able to pivot existing wearable and site optimisation technologies to assist. One.site[14], working in the area of remote inductions and contactless sign in and workforce management, have created wristbands which will alert workers if two bands come within 2 meters of each other by flashing a bright light and vibrating. WakeCap[15], originally used for detecting drivers on site falling asleep was pivoted quickly to utilise the simple data points of wearers for contact tracing. These examples demonstrates the adaptability and possibilities of the use of wearable and site optimisation technologies in the future.

[12]The Chairless Chair a lightweight, robust exoskeleton that allows for quick, easy and flexible changes between sitting, standing and walking. https://www.noonee.com/en/der-chairless-chair-2-0/

[13]The EksoWorks Vest is a shoulder and arm support exoskeleton with a headrest designed to alleviate the strain of continuously working with heavy tools above waist level. https://eksobionics.com/eksoworks/

[14] UK Connect One.Site https://ukconnect.com/services/onesite/

[15] WakeCap https://www.autodesk.com/redshift/smart-hard-hat/

8.4. Theme 4: Augmented Reality

Key Trends	Timeline	Impact
Key Trend 1: Augmented Reality (AR) for tunnel segment displacement inspection. The use of AR to inspect segment displacement during tunnelling construction can allow on-site quality inspectors to retrieve the virtual quality control baseline model which is established based on the quality standard. The baseline model can then be overlaid onto the real segment displacement in AR. Using this method, the structural safety can be automatically evaluated by measuring the differences between the baseline model and the real facility view. Also, the feedback can be used to explore and enhance the tunnel's stability to avoid significant accidents. The proposed approach might enable AR to be applied in on-site inspections more effectively. **Case 1**	**Now (0-5 years)**	**Low**
Key Trend 2: Vision-based hazard avoidance system proactively informs workers of potentially dangerous situations, enables workers to recognize and consequently avoid dangers before accidents occur through the display of augmented hazard information on a wearable device. The system comprises of three modules; a vision-based site monitoring module that utilizes image capture device and wearable devices to identify site hazards; a safety assessment module that uses captured image data and fuzzy-based reasoning to evaluate the safety level of each object; and a visualization module that provides actionable information such as hazard orientation, distance, and safety level. The safety information provided by the proposed system can mitigate hazards and improve construction site safety. **Case 2**	**Now (0-5 years)**	**Med**
Key Trend 3: Augmented Worker System (AWE) is regarded as an intelligent system that is capable of enabling intelligent design, construction, maintenance and whole-life value of building, that supports construction and infrastructure growth. The AWE is designed to drive greater certainty, safety, efficiency and sustainability through five key areas – real-time co-design and engagement; digital job guidance and skills development; process and progress monitoring and quality control; on-site visualisation and planning; and asset management and maintenance. This will allow jobs to be delivered on time, on budget, and with greater emphasis on collaboration and communication between teams and partners on projects. **Case 3**	**Next (5-10 years)**	**High**
Key Trend 4: Drones - While technology advances in the construction sector promise faster and more efficient working practices, productivity levels still remain a struggle for many contractors. Drones used in conjunction with increasingly sophisticated software have the potential to boost productivity on construction projects as suggested by drone experts and companies including Topcon, Cyberhawk and Pix4D. Specialised sensors can be quickly attached to give the drone capabilities including ultra-high resolution, multispectral and hyperspectral, thermal and oblique imaging. These could enhance extensive land and engineering surveying, precise measurement control, setting out and HD 3D laser scanning. The captured data is used to produce detailed plans, elevations and 3D BIM models that are tailored to the clients' individual requirements, as well as a range of condition and progress survey reports. **Case 4**	**Now (0-5 years)**	**High**

Augmented reality (AR) is the superimposition of digital graphics over the real world view. The users of AR may experience the enhanced world while digital information, including virtual models and contextual information, are presented and augmented with the real world. The information can be used in assisting engineers/site workers in several engineering tasks such as engineering operations and construction progress monitoring.

8.4.1 Case 1: AR technology for tunnel segment displacement inspection

The use of Augmented Reality (AR) to inspect segment displacement during tunnelling construction can allow on-site quality inspectors to retrieve the virtual quality control baseline model which is established based on the quality standard. The baseline model can then be overlaid onto the real segment displacement in AR. Using this method, the structural safety can be automatically evaluated by measuring the differences between the baseline model and the real facility view. Also, the feedback can be used to explore and enhance the tunnel's stability to avoid significant accidents. The AR-based system is established by superimposing Building Information Modelling (BIM) models onto a real structure. The difference between the BIM depiction and the real view of the facility can be measured and any changes in the segment displacement can be inspected. On-site experiments indicate that the AR-based system meets the accuracy and precision requirements for segment displacement inspection for tunnelling construction. The AR-based inspection system consists of tracking, data acquisition, display, and interaction subsystems (hardware). The live onsite scene is captured using video camera, the global coordinate and virtual camera coordinates acquired by a tracking subsystem. A virtual baseline model (3D CAD drawing) is superimposed over an onsite image in real time and the combined scene conveyed to the end users by a display subsystem. On-site experiments show that the AR-based system meets the accuracy and precision requirements for segment displacement inspection for tunnelling construction[16].

8.4.2 Case 2: Image-based construction hazard avoidance system using AR in wearable device

After any workplace accident, it is the responsibility of the safety manager to collect information about the accident context, such as working environment, types of related items/activities, movement of objects, and construction activities. Countermeasures can then be implemented based on the lagging information obtained but this does not encourage workers to take proactive actions that enables them to avoid future construction accidents. However, the availability and use of real-time leading information could be utilized for proactive accident prevention on jobsite. If the leading information is appropriately delivered to the workers, their awareness of the working circumstances can be enhanced, thereby avoiding hazardous situations. With the use of image-based safety assessment and augmented reality in a wearable device system, workers can instinctively recognize unsafe conditions and take timely and proper action against it. The system comprises of three modules: vision-based site monitoring, safety assessment, and hazard information processing and visualisation modules. The vision-based site-monitoring module acquires images and sensor data from a stationary camera and a wearable device by extracting construction site hazard information from them. The safety assessment module assesses the safety of each object using fuzzy inference logic by quantifying the safety condition of workers on site without human judgment. The hazard information is visualised using the safety condition and the worker's spatial information and processed from the perspective of the worker and displayed in augmented reality using the interface of the wearable device. The safety information provided by the proposed system can mitigate hazards and improve construction site safety. The hazard information is displayed as augmented reality in the wearable device so that a worker can effectively recognize dangerous situations without any behavioural constraints[17].

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[16] Ying Zhou, Hanbin Luo, Yiheng Yang; Implementation of augmented reality for segment displacement inspection during tunnelling construction; Automation in Construction 82 (2017) 112–121; http://dx.doi.org/10.1016/j.autcon.2017.02.007

[17] Kinam Kim, Hongjo Kim, Hyoungkwan Kim; Image-based construction hazard avoidance system using augmented reality in wearable device; Automation in Construction 83 (2017) 390–403; http://dx.doi.org/10.1016/j.autcon.2017.06.014

8.4.3 Case 3: The Augmented Worker

Carbon Dynamic and Sublime is currently pioneering the use of virtual and augmented reality for the construction industry called the 'Augmented Worker System (AWE)'. This is regarded as an intelligent system that is capable of enabling intelligent design, construction, maintenance and whole-life value of building, that supports construction and infrastructure growth. The AWE is designed to drive greater certainty, safety, efficiency and sustainability through five key areas – real-time co-design and engagement; digital job guidance and skills development; process and progress monitoring and quality control; on-site visualisation and planning; and asset management and maintenance. This will allow jobs to be delivered on time, on budget, and with greater emphasis on collaboration and communication between teams and partners on projects. The AWE will reduce the need for paper or mobile based handheld devices, thus giving workers a hands free, heads-up solution for a greater level of safety whilst providing real-time visualisation on-site. The associated benefits of AWE include reducing material wastage and time; ensuring the integrity of the final build; streamlined consistency across construction sites; enhanced worker training; and improved construction quality.

Figure 10: Augmented Worker (*Source*: https://www.carbondynamic.com/vr-ar)

8.4.4 Case 4: Using Drones in Construction

There are unique challenges that arise during the phases of construction and building projects which lead to delays and cost overages. By utilising drones and DroneDeploy[18], an organisation could save time, increase efficiency, and avoid costly budget overruns. The use of drones to inspect parts of a building that would otherwise be challenging or risky for a worker to do so can give peace of mind, and the use of drone technology can augment operations. Implementing drone technology in operations can lead to greater Quality Control (i.e. structures are built according to design specifications, with reduced human error throughout the construction phases); stronger documentation and communication around constructability issues; and improved safety (inspections of intricate sections of buildings that would be nearly impossible to examine solely with a human). The result of improved communication, greater quality control, and huge savings, could bolster more contracts for organisations adopting this technology. DroneDeploy released a new suite of drone technology features which could reduce project timelines, improve communications, make site assessment and inventories more accurate and improve safety. Project managers will be able to visualise their sites via panoramic imagery and videos, as well as overlaying plan drawings on drone imagery, highlighting grading inaccuracies, and health and safety issues. The software can also integrate imagery with CAD, BIM and other aerial or GIS software.

[18] DroneDeploy https://www.dronedeploy.com

9. Future Scenario B: Factories Run the World

Theme 5: Industrialised Construction, DfMA and Platforms
Theme 6: 3D/4D Printing
Theme 7: Robotics
Theme 8: Construction Biotechnology & Advanced Materials

9.1 Theme 5: Industrialised Construction

Key Trends	Timeline	Impact
Key Trend 1: Future Opportunities for Industrialised construction (IC) the willingness of major cities such as San Francisco, New York and London to make significant investments in new manufacturing technologies and companies is a clear sign that industrialised construction has the attention and optimism of a growing number of public stakeholders.	**Now (0-5 yrs)**	**High**
Key Trend 2: Factory-Made Housing is responding to the challenges of delivering numbers and quality. The benefits and challenges are highlighted. Examples from the UK and internationally are presented for different forms of housing solutions and new approaches. It is important to note that although there is a focus on factory-made housing, it also applies to other residential units e.g. student accommodation, schools, hospitals, prisons, build-to-rent apartments, hotels, etc. **Case Study 1: Factory-made housing solutions**	**Now (0-5 yrs)**	**High**
Key Trend 3: Platform Design for Manufacture and Assembly (P-DfMA) By procuring, not by programme or sector, but by common components, it can help construction reach the volumes that manufacturing has. Construction already incorporates manufactured products and systems into its processes. Existing products offer value to the manufacturer in the form of profits from sales while not necessarily passing that value on to the supply chain or end client. Improvements in the product drive incremental increases in value to the manufacturer (in the form of greater profits and / or market share). Current practice usually brings together a range of these systems and products, where benefits are 'external-facing' i.e. captured by the supply chain. By contrast, a platform-based approach is designed to maximise the overall efficiency and effectiveness of the whole system, creating cumulative gains for all stakeholders in the system.	**Next (5-10 yrs)**	**High**

9.1.1 Future opportunities for Industrialised construction (IC)

In the United Kingdom, the term modern methods of construction (MMC) is often used to collectively describe a number of approaches to construction (both offsite-based construction technologies and innovative onsite technologies) that offer an alternative to 'traditional' construction onsite. This research feels that the use of the term MMC is too broad and is not helpful. The term Industrialised Construction (IC) is more useful as it promotes the advancement of construction processes by employing mechanisation and automation to change how we design, manufacture, and assemble. Organisations that are involved in this area are generating the investment, strategic variety, capacity, and ambition to be worthy of serious attention across the construction sector. Research examining the trends identified four future opportunities in the area of industrialized construction[19].

1. Cities are increasingly interested in IC

Cities such as San Francisco, Vancouver, and New York have expressed explicit interest in directly funding industrialised construction ventures. Driven primarily by the need for more affordable housing, each of those city governments claims to have secured or otherwise set aside funding to start producing modular housing on their own. The willingness of these major cities to make such significant

[19] Pullen et al. (2019) A Preliminary Overview of Emerging Trends for Industrialized Construction in the United States

investments in new technologies and companies is a clear sign that industrialised construction has the attention and optimism of a growing number of public stakeholders. In the UK, particularly in London, government-driven partnerships with industrialised construction companies (see section 9.1.4: Factory-made housing solutions) to rapidly produce housing in areas of notable growth are in place.

2. Few companies appear to be involved in the operations and maintenance phase
Less than 10% of the companies involved with IC are involved in the maintenance and operations phase of their own projects. A number of the companies producing volumetric modular units offer a warranty of some sort, usually distinguishing between workmanship defects, systems defects, and structural defects. This is at least somewhat indicative of the pivot towards thinking of their units as a "product" rather than construction as a "service", but it is still far from a true extension towards opportunities in the life cycle management of that product. Warranty-based involvement in the use phase of a structure implies a purely *reactive* business mindset rather than a proactive mindset that would enable a company to benefit even after a project is delivered. This suggests there is still a significant opportunity for IC firms to expand their business model to capture value presented by a product throughout its entire life cycle.

3. Only a few companies have adopted factory automation
Similarly to the last observation, very few companies appear to have adopted any form of automation in their factories. Based on the fact that automation is still poorly defined even for the most advanced manufacturing companies in the automotive industry, this is understandable. Scaling up automated machines, even just from cars to physically larger buildings, is difficult and resource-intensive. Especially due to the variability in requirements across sectors and clients, attempting to standardise and then automate these processes can be complex. A particularly novel application of automation is in the design phase, as parametric design tools enable a large amount of design work to be performed efficiently and at scale (Generative Design at Van Wijnen). Demonstrations provided by such firms as Bryden Wood (see 9.1.4: Platform approach to Design for Manufacture and Assembly) and Project Frog in the US in partnership with AutoDesk. As the accessibility of automation tools and technologies expand independently, this is a trend is looking to continue.

4. Chance to expand integration
Though IC firms have already been shown to be more vertically integrated (involved in the maintenance and operations phase of their own projects), more opportunities for companies to vertically and horizontally integrate their business are possible[9]. These include; Shipping and distribution, Raw material acquisition, Building Inspection, & Internet of things.

9.1.2 Factory-Made Housing

The report on *Factory-Made Housing – A Solution for London*[20] provides a useful examination on the current state of play on Factory- Made housing and how the design and construction industry is responding to the challenges of delivering numbers and quality. In his foreword, Peter Murray, Chairman of New London Architecture reflects on the Harold Wilson government's failed attempt at producing 'prefabricated' homes, which still lingers to this day. He asserts that this time we have to do better. Building technology is much improved, new supply chains can lead to better quality of outcomes and, unlike the 60s when concrete was the only material available, we have a greater variety of structure, cladding and methodology at our fingertips. We also have the benefits of digital

[20] New London Architecture (2018) Factory-Made Housing – A Solution for London?

technologies which can deliver many benefits of quality, design efficiency, sustainability, flexibility and variety. Nevertheless the same issues of mass production apply – make a mistake once and you make it many times. The failures of the 1960s were a huge setback for the concept of factory-made housing, although its benefits were realised by the commercial and hotel sectors with prefabricated cladding systems and volumetric pods. Today, attitudes have changed as a result of publications such as the Farmer Review[21], the shortage of on-site labour and the huge numbers of homes that have to be delivered. It is important to note that although there is a focus on factory-made housing in this report, IC also applies to other residential units e.g. student accommodation, schools, hospitals, prisons, build-to-rent apartments, hotels, etc.

Benefits

✓ **Speed of delivery:**
As components and systems are made in a factory, they are not affected by delays to onsite construction that may be caused by adverse weather. Most importantly, fabrication for ease of assembly is reported to significantly reduce completion times from anything between 30 and 70 per cent quicker than traditional construction methods.

✓ **Controlled production leads to higher quality:**
Vastly improved materials and quality control within the factory can exponentially reduce variation and potential defects, as well as provide quality assurance and rigorous testing on aspects such as acoustic and fire performance, durability and structural resilience. Improved performance and quality may also lead to reduced energy costs and waste: the government-supported charity WRAP believes waste savings to be as much as 70 to 90 per cent.[35]

✓ **Reduced transportation and community impact:**
Reducing building times can substantially mitigate the adverse effects of noise and poor air quality on surrounding households and businesses. Most importantly, factory-made construction relies on considerably fewer deliveries to site and vehicle movements than traditional construction.

✓ **Flexibility and diversity:**
The variety of systems and materials in use mean that there is a solution for almost every site and scale of project, and the interchangeability of many components can allow greater diversity of form and typology. Modular constructions especially can be assembled and de-constructed for relocation and reuse.

✓ **Improved environmental performance:**
Factory-made building can provide significant reductions in embodied carbon and improved energy efficiency, in particular through the increased use of certified timber products.

✓ **Transforming the workforce, skills and the working environment:**
Factory-made construction can dramatically reduce labour input both onsite and offsite, with fewer workers needed to manufacture, deliver and install components – offsite housing is not as affected by the shortage of skilled labour in the construction industry. Moving production to a factory has also been proven to dramatically improve health and safety and also has the potential to transform the public view of construction, and to attract a younger and more diverse workforce.

✓ **Optimising viability of smaller sites and infill:**
As noted by the London Assembly 2017 report, factory-made building can provide significant advantages for London in terms of meeting demand for new homes via small, restricted sites, infill sites and estate intensification, as it offers reduced impacts of noise and vehicle movements and flexibility for building on irregular plots.

Barriers

✗ **Upfront costs:**
Factory-made housing may be quicker to build but to date it is not necessarily significantly cheaper than traditional construction. One of the most widely voiced concerns is the significant investment required to set up factory production (including purchase of equipment), and the consequent need to ensure a consistent supply of work to feed factory production in order to ensure efficiency and cost-effectiveness.

✗ **Lack of capacity and a diverse supply chain, and concern about skills distribution:**
There is currently limited capacity, certainly in volumetric (modular) construction in England and projects are reliant on a handful of major suppliers. Most factories are located outside London and therefore there is concern that the potential for local skills development, especially in areas of disadvantage, is being lost in London in favour of other UK regions. As Alun Macey, head of construction at Pocket Living, explains: 'the main challenge for us is trying to find a framework of contractors who are credible.'[36] This has meant that major companies are now establishing their own factories to ensure continuity and quality control.

✗ **Lack of demand and continuity of supply:**
Most factory-made projects have been relatively small scale to date. Manufacturing a product of any kind requires upfront investment and a different business model that does not necessarily fit with current procurement methods. A lack of collaboration between potential clients, especially local authorities tasked with delivering housing at scale, has prevented procurement on the scale required.

✗ **Universal standards, quality and accreditation:**
Confusion about terminology and definitions is a major issue, while there are also multiple accreditation and quality assurance schemes, and a significant lack of guidance in an easily accessible (and non-technical) form. There are also concerns raised about data transparency in this respect, with competing standards and systems currently in play.

Figure 11: Benefits and barriers to adopting a factory-made approach (*Source*: New London Architecture, 2018)

[21] Farmer, M. (2016) The Farmer Review of the UK Construction Labour Model. UK Construction Leadership Council.

9.1.3 International factory-made housing today

Streamlined manufacturing approaches, new technologies, and the advantages in increased efficiency, safety and quality that factory-made housing can provide, have led to a noticeable resurgence of global interest in this area, especially as a means of 'disrupting' the housebuilding industry, in addition to established suppliers and models. With one of the world's strongest markets, Japan has well-established providers of factory-made homes such as Daiwa House and Sekisui House, offering a diverse range from single-family, custom-built houses to large-scale rental developments. However, there are now new entrants from outside the construction market, including the retailer Muji, which, as well as developing compact, portable and prefabricated wooden cabins, has also unveiled a larger prototype, two-storey home adapted from a design by Kengo Kuma.

In Sweden – the country with by far the largest proportion of prefabricated homes – major manufacturers such as Lindbäcks, using mostly timber-framed items, can reportedly build components for about 20 multi-storey residences per week. In addition, in the 1990s the BoKlok model – a joint venture between construction company Skanska and retailer IKEA – was introduced as an alternative response to the demand for high-quality but affordable homes, of which 10,000 have now been built. In these homes, larger components such as wall panels, windows and doors are standardised, but individuality and choice for the consumer/homeowner are introduced through variations in smaller fitted elements such as drawer and cupboard fronts. Over and above this, built-in flexibility, such as potential for additional space, is provided by features such as a loft area manufactured with flooring added, and a built-in cupboard that can be replaced with a 'flat-pack' staircase, supplied by IKEA. These self-build or kit homes – selected and purchased from a dedicated supplier, which also usually constructs and installs the building – are among the best-known types of mass-produced homes in Europe and the USA. The environmentally friendly, customised but prefabricated wood and glass homes produced for over a century by German company Huf Haus have now also become popular in the UK, with over 200 built in the 2010s, but these serve the higher end of the private house market. In the USA, factory-made buildings make up about seven per cent of market share in construction, but there are well established manufacturers across the country serving regional markets, with clusters in states such as Georgia, Texas and California. Here, new tech start-ups have also started to emerge as key players in commissioning, development, production and delivery of factory-made homes. Among the most notable is Katerra, founded only in 2015 but now reportedly with investment at over $250 million, with its first factory in Phoenix, Arizona, making extensive use of BIM software to improve manufacturing processes and products. Also offering selected customisation, the company was founded on the principle that 'applying systems approaches to building development, design, and construction would remove unnecessary time and costs and a vision of a future where efficiency wouldn't have to come at the expense of quality or sustainability'. It was reported in 2017 that rocketing prices for homes in and around Silicon Valley in California have compelled Google's parent company Alphabet Inc. to order 300 apartments from a modular home start-up to serve as temporary accommodation for its employees.

Case Study 1: Factory-made housing solution

There has been increasing interest in how factory methods could provide a response to the housing crisis and how it can be used to support the regeneration of existing communities and the creation of new ones. The examples shown in the following pages demonstrate how London's built environment industries are now developing and delivering innovative and high-quality factory-made housing in a huge variety of contexts, forms and tenures, from individual houses on small sites to large-scale developments in major areas of opportunity.

Figure 12: FAB HOUSE, the Plateau, North Shields, Tyne and Wear (Source: New London Architecture, 2018)

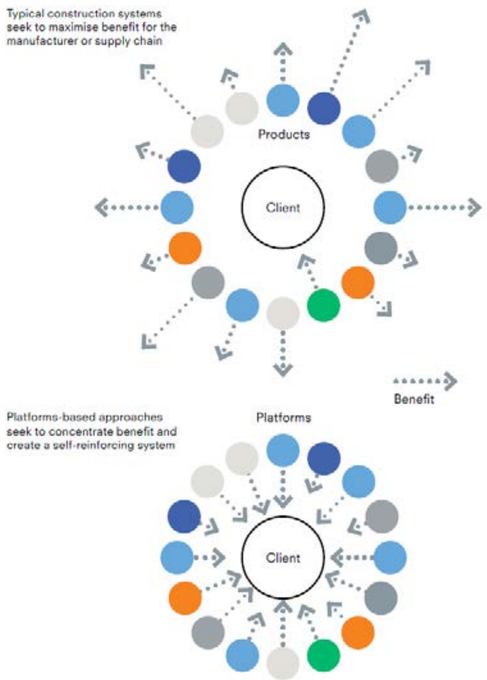
The brief for Fab House was to develop a new offsite manufactured home typology that is affordable, elegant and spacious, using modular construction. The design embraces efficiency, with the whole house assembled on a production line, reducing time, disruption and material waste on site, whilst also incorporating design strategies such as exposing ceiling joists to create more height than typical modular homes. Fab House's cladding is mounted away from the structure, leaving a void for all services to run outside the house which reduces the need for follow-on trades to enter each property. The gap also aesthetically creates depth and a sense of permanence. Fab House represents a low-cost prototype which can be constructed quickly with little waste and at scale, complementing London's Victorian terraces.

(Source: New London Architecture, 2018)

9.1.4 Platform approach to Design for Manufacture and Assembly (P-DfMA)

Design for Manufacture and Assembly (DfMA) is a design approach that focuses on ease of manufacture and efficiency of assembly. By simplifying the design of a product it is possible to manufacture and assemble it more efficiently, in the minimum time and at a lower cost. Platforms are a giant "kit of parts" - sets of pre-engineered components that go together in well-defined ways to produce products or structures very efficiently. Flexibility is designed in, so that a single platform can produce an almost infinite range of different structures in a manufacturing technique called mass customisation. A car chassis, for example acts as a platform and may form the basis of every model in a manufacturer's range. The transport container and the iPhone app store are other examples.

You'd never open a factory to meet one order, however big, only to close it again. Continuity and volume of demand is vital, and construction needs that to emulate the efficiencies of manufacturing. By procuring, not by programme or sector, but by common components, it can help construction reach the volumes that manufacturing has. Construction already incorporates manufactured products and systems into its processes. This raises the question of how platforms can offer significant benefits over and above these existing systems. Existing products offer value to the manufacturer in the form of profits from sales while not necessarily passing that value on to the supply chain or end client. Improvements in the product drive incremental increases in value to the manufacturer (in the form of greater profits and / or market share). Existing construction brings together a range of these systems and products, where benefits are 'external-facing' i.e. captured by the supply chain. By contrast, a platform-based approach is designed to maximise the overall efficiency and effectiveness of the whole system, creating cumulative gains[22].



If platform construction is like a giant kit of parts, the selection of those parts must lower the barrier to entry and be capable of:

• Manufacture at scale with existing skills, processes and tools.

• Rigorous quality assurance through manufacture, assembly and pre-testing to maintain consistency from construction through to operation using local, semi-skilled labour.

• A high level of repeatability and use of materials that are already available

• Platform construction will allow DfMA to be rolled out at scale, and create training programmes that could facilitate the creation of new apprenticeships and skill-sets

Figure 13: Product v Platform (Source: Bryden Wood, 2018)

However, above all, you need customers with a substantial pipeline, or groups willing to work together or industry standardisation for this to happen. There is positive signs that the UK Government is pushing ahead with the platform approach to design for manufacture and assembly (P-DfMA) which it has labelled as a "new approach to building" by creating a set of digitally designed components across multiple types of built asset. For example, a single component could be used as part of a school, hospital, prison building or station.

The Infrastructure and Projects Authority (IPA) will outline the next steps in its Transforming Infrastructure Performance (TIP) strategy, including a platform approach to design for manufacture and assembly (P-DfMA). IPA are currently working on the details of P-DfMA. Current examples include collaboration between Highways England, Transport for London, Network Rail and industry to rationalise the various designs for footbridges. The emergence of standardised configurator apps, which pull together information such as geospatial data, planning rules and Building Regulations, and help automate the design process. Examples include Bryden Wood's Prism, developed for housing with the Mayor of London; Seismic, created for primary schools with the Department for Education: and Highways England's Rapid Engineering Model.

The next step is to increase the codification of government specifications, applying open data principles, so that these approaches can be applied more broadly across government procurement to more effectively provide a pipeline to support increased manufacturing approaches in the construction industry.

[22] Bryden Wood (2018) Platforms: Bridging the gap between construction + manufacturing. Centre for Digital Built Britain.

9.2 Theme 6: 3D/4D Printing

Key Trends	Timeline	Impact
Key Trend 1: 3D Glass Printing - uses an additive manufacturing platform designed to print optically transparent glass. The Glass 3D Printing project synthesizes modern technologies, with age-old established glass tools and technologies producing novel glass structures with numerous potential applications. **Case 1**	**Next (5-10 years)**	**Med**
Key Trend 2: 3D-printed bridges – The first 3D-printed concrete bridge created in the Netherlands at Gemert is a crossing for cyclists by construction company BAM Infra and claims to take the weight of 40 lorries. It took three months for robots to print the 800 layers of pre-stressed, reinforced concrete in sections in the Eindhoven University of Technology laboratory. The unique design uses less concrete than a traditional poured concrete bridge, making it a more sustainable construction process. **Case 2**	**Next (5-10 years)**	**Med**
Key Trend 2: 3D-printed neighbourhood houses - In Southern Mexico, a giant, 33-foot-long 3D printer recently built the walls of the first homes in the world's first 3D-printed neighbourhood. **New Story** partnered with **Icon**, a construction tech company based in Austin, to begin developing a 3D printer rugged enough to work even in the most challenging conditions. The printer works by squirting a concrete mixture in layers to build floors and walls. Software monitors the weather conditions, and the machine can adjust the mixture a little bit in accordance with the viscosity required to have the same print quality throughout the day. **Case 3**	**Future (10-20 years)**	**High**

3D printing (sometimes referred to as Additive Manufacturing (AM)) is the computer-controlled sequential layering of materials to create three-dimensional shapes. Additive manufacturing (AM) is considered as a group of emerging techniques for fabricating three-dimensional (3D) structures directly from a digital model. Unlike conventional industrial manufacturing processes, AM processes build a finished structure in successive layers with less waste material. Since its emergence 30 years ago, AM technologies have been successfully applied in a wide range of industries including aerospace, automotive, biomedical, consumer and food. 3D printing is gaining popularity in construction industry and when compared with conventional construction processes, the application of 3D techniques in construction industry may reduce labour requirements which would result in a decreased construction cost and an increased level of safety; reduce on-site construction time by operating at a constant rate; minimize the chance of errors by highly precise material deposition; and increase architectural freedom which would enable more sophisticated designs for structural and aesthetic purposes.

The implications for the construction industry adopting 3D printing is considered beneficial in terms of its capability to enhance construction lead times, product quality and reliability, production flexibility, productivity and economies of scale, supply chain sustainability, new business models and opportunities for new suppliers. 3D printing has the ability to support increased product customization, which in turn requires the customer to be actively involved in the definition of their product.

The two techniques generally adopted in construction are divided into - Extrusion printing and Powder printing. The extrusion printing technique is analogous to the Fused Deposition Modelling (FDM) method by extruding cementitious material from a nozzle mounted on a gantry to print a structure layer by layer. The powder printing technique, also named powder-based three dimensional printing, is another typical AM process that creates accurate structures with complex geometries by depositing binder liquid (or "Ink") selectively into powder bed to bind powder where it impacts the bed. Although these two techniques are designed for construction purposes with many similarities, they however have distinct features in the construction industry. The extrusion printing technique is aimed at on-site construction applications such as large-scale building components with complex geometries, whilst the powder printing technique is an off-site process designed to manufacture precast components. The powder-based 3D is considered suitable for small-scale building components e.g. panels, permanent formworks and interior structures that can be easily assembled on site. A major challenge for 3D concrete printing is that it requires skilled workers with experience to integrate robotic and civil work together. 3D printing of full-scale construction components is still an emerging technology and as an alternative construction method, the potentials are unlimited. The main challenge that is associated with material deposition method (FDM) is to develop an appropriate material that can be extruded continuously and stacked up over one another without initiating any deformation in the bottom bead layers.

9.2.1 Case 1: 3D Glass Printing

A first of its kind optically transparent glass printing process called G3DP developed in collaboration with MIT's Glass Lab uses an additive manufacturing platform designed to print optically transparent glass. The tunability enabled by geometrical and optical variation driven by form, transparency and colour variation can drive; limit or control light transmission, reflection and refraction, and therefore carries significant implications for all things glass. The platform is based on a dual heated chamber concept. The upper chamber acts as a Kiln Cartridge while the lower chamber serves to anneal the structures. The Kiln Cartridge operates at approximately 1900°F and can contain sufficient material to build a single architectural component. The molten material gets funnelled through an alumina-zircon-silica nozzle. The Glass 3D Printing project synthesizes modern technologies, with age-old established glass tools and technologies producing novel glass structures with numerous potential applications as ornaments and artefacts.

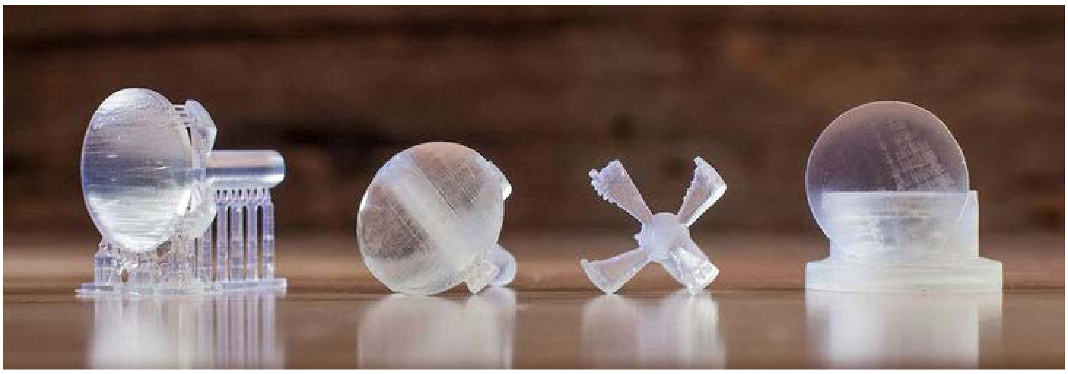


Figure 14: Optically Transparent Glass 3D Printing Process (Source: [Kadvacorp]())

9.2.2 Case 2: The 3D-printed bridges

3D printing is particularly useful for prototyping and for the manufacture of geometrically complex components. The future of construction and the use of 3D printing in construction is a nascent technology still within the learning and experimental phase. However, this technology has been used by Weber Beamix and BAM Infra with other stakeholders in the development of the cycle bridge in Gemert, Netherlands. Eindhoven University of Technology and BAM Infra built the bridge with special mortar developed by Weber Beamix. The bicycle bridge is made of pre-stressed and reinforced concrete and can carry as many as forty trucks. The bridge consists of about 800 printed layers that was assembled on site. 3D printing is often cheaper and faster than the traditional way of building with less preparation required, less material needed and less is thrown away.

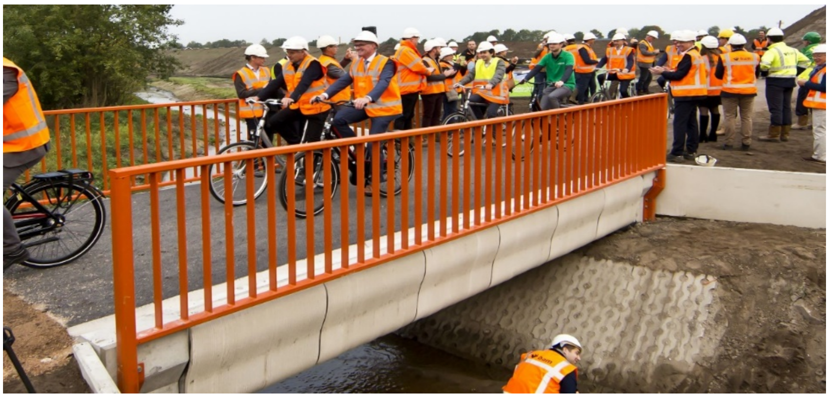


Figure 15: The 3D-printed bicycle bridge in Gemert (*Source*: Weber)

9.2.3 Case 3: 3D-printed Neighbourhood Houses

A giant 3D printer is currently printing out new homes in rural Mexico, with each one taking 24 hours. In Southern Mexico, a giant, 33-foot-long 3D printer recently built the walls of the first homes in the world's first 3D-printed neighbourhood. The 500 sq ft houses were finished with roofs, windows, and interiors. The new construction process could be part of the solution for affordable housing in some of the poorest communities in the world. **New Story** partnered with **Icon**, a construction tech company based in Austin, Texas to begin developing a 3D printer rugged enough to work even in the most challenging conditions.

Figure 16: World's first 3D printed neighbourhood (*Source*: Iconbuild)

The new Mexican neighbourhood with 50 homes, is the first community to use this type of technology at scale. The printer works by squirting a concrete mixture in layers to build floors and walls. Software monitors the weather conditions, and the machine can adjust the mixture a little bit in accordance with the viscosity required to have the same print quality throughout the day. To make it even more efficient, it's possible to print multiple houses simultaneously.

9.3 Theme 7: Robotics

Key Trends	Timeline	Impact
Key Trend 1: Construction Robots are currently limited. There are 3D-printing robots that can build on demand, robots for brick-laying and masonry, and even robots that lay an entire street at one time. There are also inspection robots such as Boston Dynamics' Spot.	**Next (5-10 years)**	**Med**
Key Trend 2: Swarms Robotics - large groups of simple agents are given free reign by working together to allow them to tackle otherwise impossible tasks. Rows of robotic arms on a factory production line, replacing rows of human workers. The more exciting prospect is to see large swarms of robots cooperating and acting as a powerful problem-solver, is now meeting enabling technologies in low-power sensors and computation, advanced batteries and manufacturing. Swarm robotics is at a tipping point: it will become part of our reality over the next ten years.	**Future (10-20 years)**	**High**
Key Trend 3: Intelligent Robots - we will see a future where we're going to have a Cambrian explosion of robot form factors. Currently, each robot is kind of an island onto itself but in the future they will be able to work as a team in a highly networked system that does not require pre-programming. The construction worker in the future will not be a manual labourer but will be a technologist using automation tools working with a robot that is highly sensed of its environment that is adaptive to the tasks rather than receiving explicit execution instructions	**Next (5-10 years)**	**Med**

9.3.1 Construction Robots

Different types of construction robots are currently available. First is a 3D-printing robot that can build on demand using a mobile robotic arm controlling a 3D-printer along with a set of programmed instructions. This technology is also being used for building bridges, with the first ever 3D printed bridge recently being built in the Netherlands by MX3D. This combination of 3D printing and industrial robots is providing some of the most promising automation technology.

Figure 17: 3D metal printed bridge (Source: MX3D)

There are also construction robots for brick-laying and masonry, and even robots that lay an entire street at one time. These types of robots dramatically improve the speed and quality of construction work. Construction Robotics' SAM100 masonry robot can lay up to 350 bricks per hour in either a standard brick pattern or soldier courses. That is much faster than most, if not all, human bricklayers.

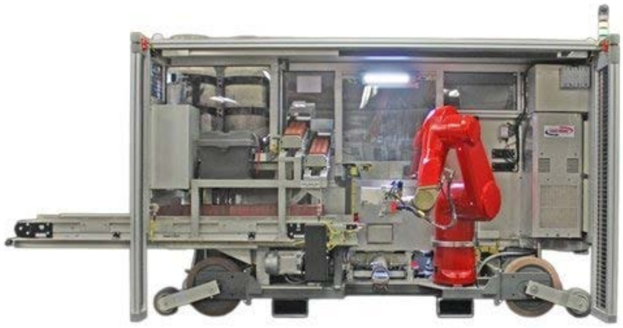


Figure 18: SAM100 (Semi-Automated Mason) brick laying robot (*Source*: Construction Robotics)

Boston Dynamics' Spot is being targeted as an inspection that can be used on construction sites. Spot can walk, trot, avoid obstacles, climb stairs, and much more. The robot's hardware is almost completely custom, with powerful compute boards for control, and five sensor modules located on every side of Spot's body, allowing it to survey the space around itself from any direction. The legs are powered by 12 custom motors with a reduction, with a top speed of 1.6 meters per second. The robot can operate for 90 minutes on a charge. In addition to the basic configuration, you can integrate up to 14 kilograms of extra hardware to a payload interface. Among the payload packages Boston Dynamics plans to offer are a 6 degrees-of-freedom arm, a version of which has a ring of cameras called SpotCam that could be used to create Street View–type images inside buildings.

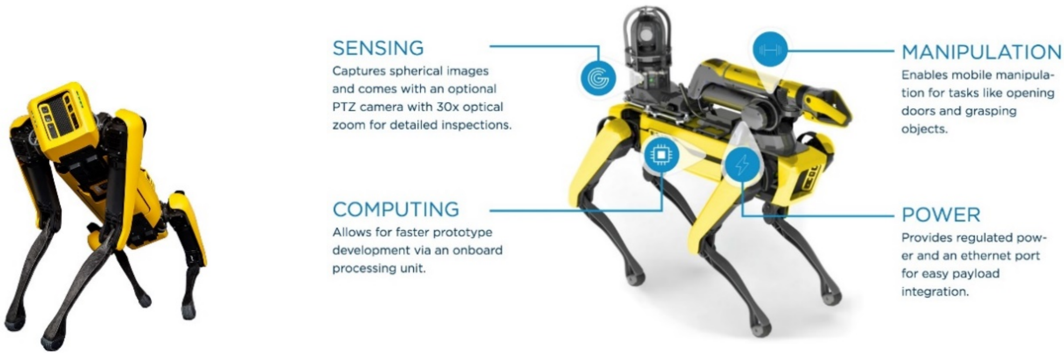


Figure 19: Boston Dynamics' Spot inspection robot (*Source*: Boston Dynamics)

As a highly unautomated industry, construction robots will have a major impact on the construction industry. As construction companies look to automate more and more tasks for the sake of efficiency and productivity, demand for construction robots will grow steadily.

9.3.2 Swarms Robotics

The way to make robots co-operate is to learn from the animal kingdom and working together will allow them to tackle otherwise impossible tasks. In his Nesta Tipping Point Prize winning essay on Swarm robotics in 2019, Dr Edmund Hunt sees the appeal of swarm engineering lies in the transformative capabilities that emerge when large groups of simple agents are given free reign.

But that’s just one way of designing and deploying robots, and perhaps not even the one with the most potential. The more exciting prospect is that over the next decade we will start to see large swarms of robots cooperating. Our scientific understanding of collectives in biology – from cells to animal groups – has greatly advanced over the past 20 years. The underlying theory of swarms, increasingly entertained by engineers as a powerful problem-solver, is now meeting enabling technologies in low-power sensors and computation, advanced batteries and manufacturing. This may result in houses being constructed brick-by-brick by a swarm of robot builders, an end to costly and disruptive roadworks or possibly ‘self-healing’ cities.

Swarm robotics is at a tipping point: it will become part of our reality over the next ten years.

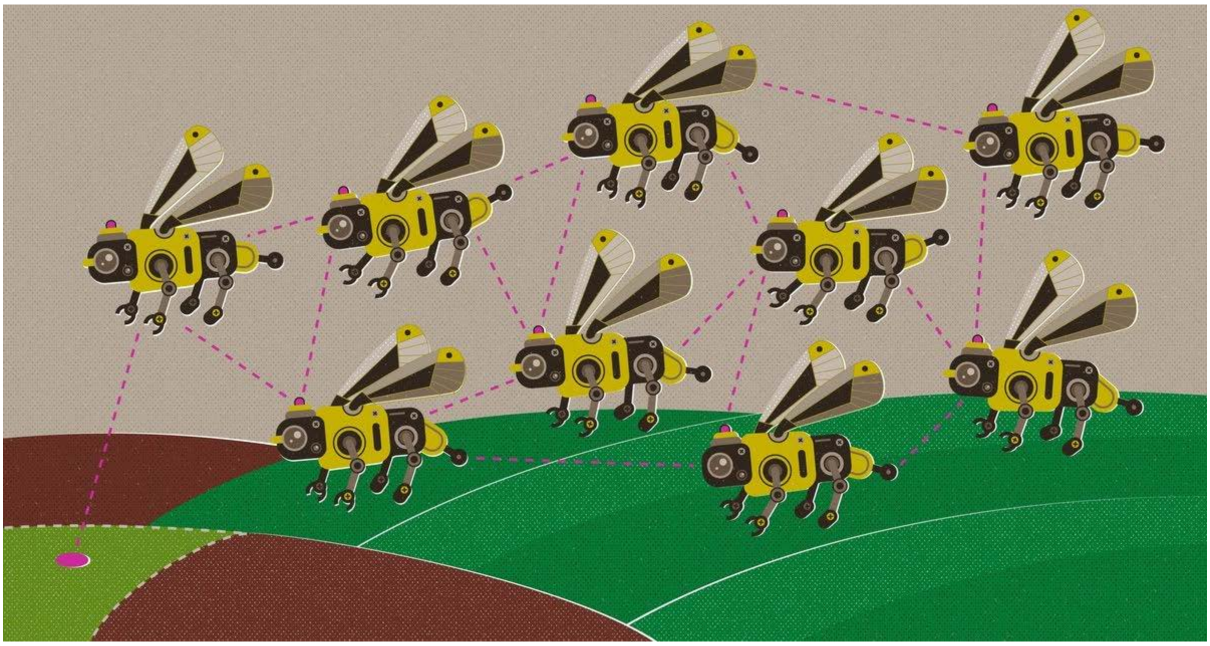


Figure 20: Swarm Robotics (Source: Nesta)

9.3.3 Insights on the Future of Robotics - Erin Bradner (Director of Robotics, Autodesk)

“We envision the future where making with robots is a natural extension of design. What we want to do is really shorten this gap between design, and make. What architects and engineers care about is not the digital representation of their idea but the physical representation. We want to enable people in any industry to partner with robots using a tool, intuitive adaptive tools. So adaptivity is really a key word for me because what I'm looking to do is mature robotics, really bringing us out of what we would call the Dark Ages, in which every robot motion is currently described explicitly and pre-programmed and towards machine learning.

What we see is a future where robots are able to execute tasks adaptively because the environment may change. The task may slightly change when you're talking about a customised artefact that you might be producing on a manufacturing line. We see a future where machine learning is simply far easier to implement than it is today, both from a technological standpoint, so you don't need to know cloud computing and or edge computing and you don't require a masters or a PhD to implement some kind of machine learning system on a robot. Robots of the future will not simply be mechanical devices, they will have sensors, they will minimally have sight, and then some sense of touch with torque or force sensors. That's going to enable them to operate in a closed loop controlling capacity, meaning they can sense and adapt their workflow. This is maturing the paradigm from a pre-programmed motion paradigm to one in which a robot senses, plans, and then acts.

You've no doubt heard of the three "Ds" in construction, the work is dirty, dull, dangerous. I'm wholly focused on robots but you know robotic automation can mitigate the cognitive risk of dull tasks and mitigate the physical risks of dirty and dangerous tasks, making them ideal for inspection robots. We see a future where we're going to have a Cambrian explosion of robot form factors. So right now what we are researching is six axis industrial arms because that's what Autodesk customers have. But we know that there will be a wide variety of form factors of robots in the future and that's going to bring both advantages and disadvantages. We spoke with a construction customer a month ago and he said, "Okay, great, so if I have one robot for painting and one robot for welding steel beams and another robot for 3D scanning then what am I going to do with all these robots? Where do I store them? We already have material storage challenges on every construction site."

There are multiple challenges. Currently, each robot is kind of an island onto itself but in the future they will be able to work as a team in a highly networked system that does not require pre-programming. Ease of use is a challenge, and I think it's easy to dismiss since we are seeing better user interfaces on robots today. But the challenge of using robots starts from calibration: the robot needs to know where it is relative to everything else in this space. Every time we get a robotics project going we underestimate how long it takes to just calibrate the system and calibrate the sensors. Hardware and software integration is a challenge. Getting a robot to understand what it's making is also a huge challenge. What's difficult is identifying the points in a 3D model that are meaningful to a robot. That's a challenge. In 20 years time, what I really hope is that we will have a parallel track for construction workers where they are gaining technological or technology expertise. So I think the construction worker in the future will be using technology as well as conventional tools. Robots on construction sites in the future will sense their environment, have closed loop control, and be adaptive to their task. Construction workers will be able to give robots tasks rather than explicit execution instruction".

9.4 Theme 8: Construction Biotechnology & Advanced Materials

Key Trends	Timeline	Impact
Key Trend 1: Construction Biotechnology looks at how organic, biodegradable materials could be combined to create objects on an architectural scale. The material itself is a living material, it sweats, it grows, it expands and it smells. It could augment the relationship between built, natural, and biological environments by employing design principles inspired and engineered by nature, and implementing them in the invention of novel design technologies. Areas of application include architectural design as well as the design of new technologies for digital fabrication and construction. This level of "environmental programming" can in the future enable the construction of structures that modify their properties relative to the season: even small alterations to the molecular composition of bio-composites can have a dramatic impact on their design and their decay. Case Study: **Aguahoja I**	**Future (10-20 years)**	**Med**
Key Trend 2: Graphene - by compressing and fusing flakes of graphene, a two-dimensional form of carbon, researchers at MIT have developed a new material that can have a strength 10 times that of steel. Many other possible applications of the material could eventually be feasible for uses that require a combination of extreme strength and light weight. For example, concrete for a structure such as a bridge might be made with this porous geometry, providing comparable strength with a fraction of the weight. This approach will have the additional benefit of providing good insulation due to the large amount of enclosed airspace within it.	**Next (5-10 years)**	**High**
Key Trend 3: Advancements in Concrete focus on the reduction of cement in concrete mixtures. Using an electrochemical method that captures CO2 before it is released, researchers are proposing using the sequestered carbon in the fuel and drinks industry. Using nano-platelets extracted from carrots and root vegetables to enhance concrete mixes. Another trend of "bioreceptive concrete" which sees structural concrete layered with materials to encourage the growth of CO2-absorbing moss and lichen. Glass Fibre Reinforced Concrete is also enabling the moulding of thinner and thus lighter façade pieces. Other advancements such as KnitCrete formwork technology, a cable-net and fabric formwork system and concrete floor slabs with a thickness of just 2cm without the need for steel reinforcing and 70% lighter is also being developed.	**Next (5-10 years)**	**High**

9.4.1 Construction Biotechnology

Biotechnology could revolutionise the construction industry. According to the Waste & Resources Action Programme (WRAP), Construction tops the list of one of the most environmentally damaging industries. Construction Biotechnology is a new scientific and engineering discipline which focuses on the development of construction processes mediated by microbes and biotechnologies for the production of construction biomaterials (naturally-derived originating from plant or animal sources). Biomaterials most commonly used in UK construction include solid timber, timber products such as wood-based panels, cellulose, plant fibres and animal fibres. The products of construction biotechnologies are usually low cost, sustainable, and environmentally friendly microbial biocements and biogrouts used for ground improvement. The implementation of construction biotechnologies could provide significant economic and environmental benefits.

Case Study - Aguahoja I

Mediated Matter Group, which is part of MIT Media Lab and headed by Neri Oxman, digitally designed and robotically fabricated the structure using materials derived from apples, trees, insect exoskeletons and bones. The project involved robotically printing a five-metre-tall pavilion out of a biocomposite made of pectin, cellulose, chitosan and calcium carbonate. Aguahoja I is a robotically fabricated structure composed of pectin, cellulose, calcium carbonate and chitosan.

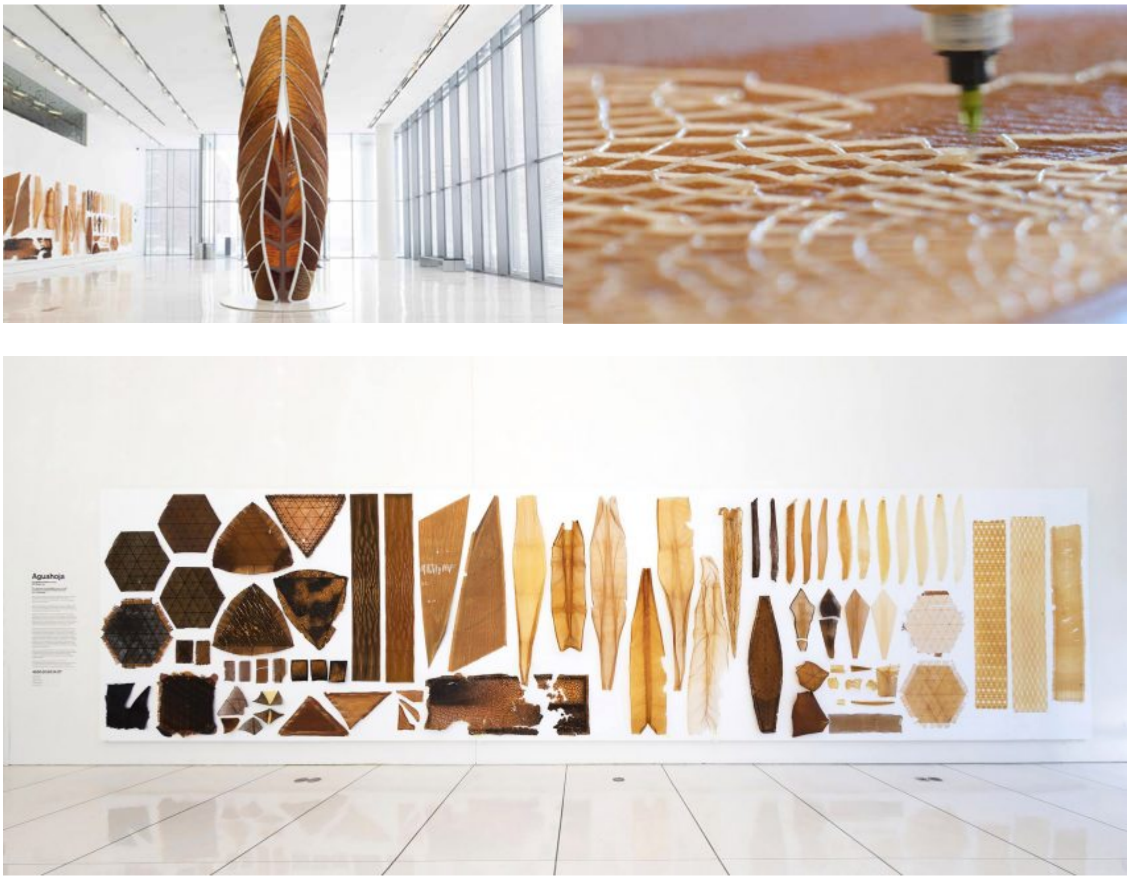


Figure 21: Aguahoja I, MIT Media Lab, Mediated Matter Group (Source: Olivia Ladanyi, 2019)

The Aguahoja project[23], which means "water-leaf," explores how sustainable composite materials extracted from living plants and animals could eventually be used at an architectural scale. The biocomposite structure is soluble, meaning the raw materials can be separated and safely biodegraded by applying water. The project demonstrated how organic, biodegradable materials could be combined to create objects on an architectural scale. The material itself is a living material, it sweats, it grows, it expands, it smells, so it's coming with all of these new attributes that you would not find in a piece of design that would usually be glossy or shiny. Part of MIT Media Lab, Mediated Matter Group attempts to apply the intrinsic intelligence of natural ecologies to the way that we design and fabricate the built environment.

[23] Olivia Ladanyi (2019) Aguahoja I won design project of the year at Dezeen Awards 2019, Dezeen. https://www.dezeen.com/2019/12/23/aguahoja-i-dezeen-awards-2019-movie/

9.4.2 Advanced Materials

9.4.2.1 Graphene

A team of researchers at MIT has designed one of the strongest lightweight materials known, by compressing and fusing flakes of graphene, a two-dimensional form of carbon[24]. The new material, a sponge-like configuration with a density of just 5 percent, can have a strength 10 times that of steel. In its two-dimensional form, graphene is thought to be the strongest of all known materials. But researchers until now have had a hard time translating that two-dimensional strength into useful three-dimensional materials. The new findings show that the crucial aspect of the new 3-D forms has more to do with their unusual geometrical configuration than with the material itself, which suggests that similar strong, lightweight materials could be made from a variety of materials by creating similar geometric features.

Many other possible applications of the material could eventually be feasible, the researchers say, for uses that require a combination of extreme strength and light weight. The unusual geometric shapes that graphene naturally forms under heat and pressure look something like a Nerf ball — round, but full of holes. The same geometry could even be applied to large-scale structural materials, they suggest. For example, concrete for a structure such as a bridge might be made with this porous geometry, providing comparable strength with a fraction of the weight. This approach would have the additional benefit of providing good insulation because of the large amount of enclosed airspace within it. The material might also find application in a variety of applications.

9.4.2.2 Advancements in Concrete

Many innovations in concrete focus on the reduction of cement in concrete mixtures. MIT researchers revealed an experimental method of manufacturing cement while eliminating CO2 emissions[25]. Using an electrochemical method that captures CO2 before it is released, the team proposes using the sequestered carbon in the fuel and drinks industry. This is still at a laboratory demonstration stage.

A related stem of innovation comes from integrating bio-based materials and elements into concrete mixtures. Recently, researchers at Lancaster University in the UK unveiled a novel approach of using nanoplatelets extracted from carrots and root vegetables to enhance concrete mixes[26]. Another trend of “bioreceptive concrete” which sees structural concrete layered with materials to encourage the growth of CO2-absorbing moss and lichen. An alternative mixture which is already entering mainstream architecture is GFRC (Glass Fiber Reinforced Concrete). The material consists of a mortar made of concrete, sand, alkali-resistant glass fiber and water. Plasticity is one of the main qualities of GFRC, enabling the molding of thinner and thus lighter façade pieces. For example, this material is used in the cladding of the Heydar Aliyev Centre by Zaha Hadid Architects, and it is also being used to implement the complex forms of Gaudi’s Church of the Sagrada Familia.

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[24] Chandler, D.L. (2017) Researchers design one of the strongest, lightest materials known Porous, 3-D forms of graphene developed at MIT can be 10 times as strong as steel but much lighter, MIT News. https://news.mit.edu/2017/3-d-graphene-strongest-lightest-materials-0106

[25] Chandler, D.L. (2019) New approach suggests path to emissions-free cement, MIT News. http://news.mit.edu/2019/carbon-dioxide-emissions-free-cement-0916?utm_medium=website&utm_source=archdaily.com

[26] Walsh, N.P. (2018) Could Carrots Make Concrete Stronger and Greener? ArchDaily. https://www.archdaily.com/900003/could-carrots-make-concrete-stronger-and-greener/

As well as embracing GFRC in the construction process, Zaha Hadid Architects has also exhibited a more novel approach to concrete, having unveiled a 3D-knitted shell at the Museo Universitario Arte Contemporaneo in Mexico City. Forming part of ZHA's first exhibition in Latin America, KnitCandela "pays homage to the Spanish-Mexican architect and engineer Felix Candela" by reimagining his inventive concrete shell structures through an innovative KnitCrete formwork technology[27]. With a knitting time of 36 hours, the cable-net and fabric formwork system allows for expressive, freeform concrete surfaces to be constructed without the need for molds. The knitted fabric for KnitCandela, developed at ETH Zurich, was transported from Mexico to Switzerland in two checked suitcases, totalling 350 kilometers of yarn weighing 25 kilograms. The pavilion's thin, double-curved concrete shells hence weigh only 5 tonnes in total, despite a surface area of 50 square meters.

Figure 22: Heydar Aliyev Centre / Zaha Hadid Architects. (*Source*: Walsh, 2019)

While playing a crucial role in the KnitCrete technology between ZHA's exhibition, ETH Zurich has been at the forefront of a number of innovations concerning concrete. With the intention of maximizing available space and avoiding steep construction costs, researchers from ETH Zurich's Department of Architecture have devised a concrete floor slab that with a thickness of a mere 2cm, remains load-bearing and simultaneously sustainable. As opposed to traditional concrete floors that are evidently flat, these slabs are designed to arch in order to support major loads, reminiscent of the vaulted ceilings found in Gothic cathedrals. Without the need for steel reinforcing and with less concrete, the production of CO2 is minimized and the resulting 2cm floors are 70% lighter than their typical concrete counterparts.

[27] Walsh, N.P. (2019) ETH Zurich Develops 3D-Printed Concrete Columns, ArchDaily. https://www.archdaily.com/921635/eth-zurich-develops-3d-printed-concrete-columns/

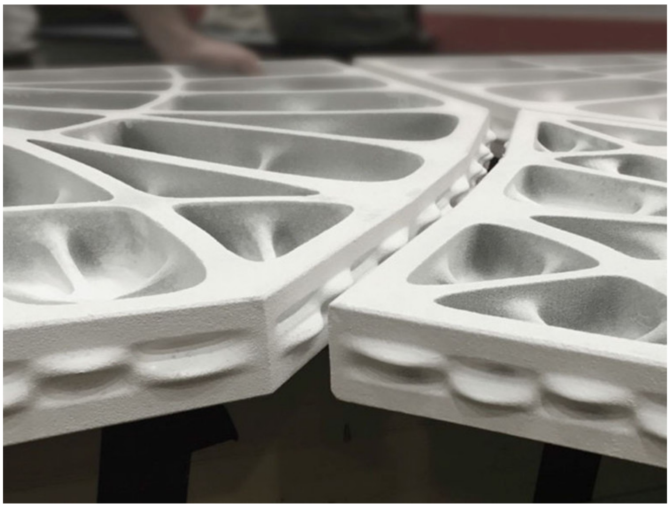

Figure 23: Gothic Construction Techniques (*Source*: Walsh, 2019)

More recently, the institution has also showcased the potential of 3D printed concrete. The "Concrete Choreography" installation at Riom, Switzerland, presented the first robotically 3D printed concrete stage, consisting of columns fabricated without formwork[17]. The installation features nine 2.7-meter-tall columns, individually designed with custom software and fabricated with a new robotic 3D printing process developed by ETH Zurich with the support of NCCR DFAB. The hollow concrete structures are printed to allow materials to be strategically used, allowing for a more sustainable approach to concrete architecture. In addition, the computationally-designed material ornament and surface texture exemplify the versatility and significant aesthetic potential 3D concrete printing holds when used in large scale structures.

It is clear, therefore, that there are numerous potential futures for concrete to continue as a material of choice in the design and construction industry. Having shaped our cities for centuries, and facilitating rapid expansions and new heights, it is now time to consider how materials such as concrete can continue to support innovation, by being the subject of innovation themselves. The challenge for the construction industry will be to ensure that such innovative solutions, with the potential to fundamentally change how we do or do not use concrete, begins to become accepted in a traditionally conservative industry. Otherwise, it is clear that the environmental impact of concrete as it is currently constituted will see the material overtaken by its green competitors.

10. Future Scenario C: A Green Reboot

Theme 9: Sustainable Design & Climate Change
Theme 10: Smart Cities (National Digital Twin)

10.1 Theme 9: Sustainable Design & Climate Change

Key Trends	Timeline	Impact
Key Trend 1: United Nations Sustainable Development Goals (UNSDG) These were introduced at the start of this report in Section 1. The UNSDGs provide a blueprint to achieve a better and more sustainable future for all. The 17 Goals are all interconnected and address the global challenges we face.	**Now (0-5 years)**	**High**
Key Trend 2: Committee on Climate Change provides independent advice to government on building a low-carbon economy and preparing for climate change under the Climate Change Act which targets to reduce UK greenhouse gas emissions by at least 80% relative to 1990 by 2050.	**Now (0-5 years)**	**High**
Key Trend 3: Net Zero Carbon Buildings - The UK Green Building Council (2019) publication "Net Zero Carbon Buildings: A Framework Definition" provides an overarching framework of consistent principles and metrics that can be used as a tool for businesses to drive the transition to a net zero carbon built environment. It provides guidance on how to demonstrate how a building has achieved net zero carbon status.	**Now (0-5 years)**	**High**

In the UK, the operation of buildings accounts for around 30 per cent of emissions, mainly from heating, cooling and electricity use. While for new buildings, the embodied emissions from construction can account for up to half of the carbon impacts associated with the building over its lifecycle. The term 'zero carbon' has a particular connotation in recent years of UK Government climate policy. Historical 'zero carbon' policies focused only on operational energy and modelled performance in new buildings but there is now a drive to include in-use performance and to encompass the whole life carbon impacts of both new and, crucially, existing homes and buildings.

In addition to committing to the delivery of the ***United Nations Sustainable Development Goals***, the UK Government and the devolved administrations committed to the Net Zero target as recommended by the ***Committee on Climate Change***, which provides independent advice to government on building a low-carbon economy and preparing for climate change. This will be actioned through climate change mitigation, specifically under the Climate Change Act. At the core of the Act is the 2050 target to reduce UK greenhouse gas emissions by at least 80% relative to 1990, and the system of carbon budgets that provide five-year stepping stones to the 2050 target. They can be met through a combination of energy efficiency improvement, investment in low-carbon power generation, phased electrification of heat and surface transport, and targeted use of sustainable biofuels. The Act also requires the government to build the resilience of the country to climate change, and as required has published a climate change risk assessment, and National Adaptation Programme.

What changed are needed?

- resource and energy efficiency, that reduce demand for energy across the economy
- societal choices that lead to a lower demand for carbon-intensive activities
- extensive electrification, particularly of transport and heating, supported by a major expansion of renewable and other low-carbon power generation

- development of a hydrogen economy to service demands for some industrial processes, for energy-dense applications in long-distance HGVs and ships, and for electricity and heating in peak periods
- carbon capture and storage (CCS) in industry, with bioenergy (for GHG removal from the atmosphere), and very likely for hydrogen and electricity production.

The UK Green Building Council (2019) publication "Net Zero Carbon Buildings: A Framework Definition" provides an overarching framework of consistent principles and metrics that can be integrated into policy, but primarily can be used as a tool for businesses to drive the transition to a net zero carbon built environment. The framework has been developed by an industry task group of businesses, trade associations and non-profit organisations, undertaken in a spirit of collaboration and consensus-building. It provides guidance on the definition of net zero carbon buildings – both homes and non-domestic – and a way to demonstrate how a building has achieved net zero carbon status. It focuses on carbon impacts that can be readily measured and mitigated today – operational energy and embodied impacts of construction.

The Framework overarching principles

1. Polluter pays

The cost of addressing emissions should be borne by the actors who are responsible for creating them. As far as possible, any emissions should be measured and offset at the time they occur, to encourage reduction and mitigation as first steps before considering any form of offsetting. Where appropriate, operational energy use should be delineated between the actors who have responsibility and/or the ability to influence energy use.

2. Improve measurement and transparency

As far as possible, building emissions should be based on measurement rather than estimates and using the most accurate data available. Public disclosure of emissions should also provide transparency about how this information has been collected and the approach taken by a building to achieve net zero carbon. Operational energy performance should be based on measured in-use energy consumption and generation, while whole life carbon assessments of construction impacts should be verified and updated at the point of completion.

3. Encourage action today and tighten requirements over time

A net zero carbon built environment will require a whole life carbon approach to net zero carbon buildings, but the framework outlined here is limited in scope to areas where measurement and mitigation are feasible today – operational energy use and embodied carbon from construction. High level principles and metrics have been set out for these areas to guide actions and encourage public disclosure of data. Future development of the framework will introduce more robust requirements and targets, for example minimum energy efficiency targets, and expand the scope to take a net zero whole life carbon approach. The framework should provide an incentive for the use of approaches such as the BSRIA Soft Landings Framework and the Better Buildings Partnership Design for Performance initiative. The move towards in-use performance will see a move in the industry towards 'performance contracts' that are based on achieving specified outcomes. This will create opportunities in areas such as building management which will be examined in ***Paper 2: Facilities Management***.

10.2 Theme 10: Smart Cities & National Digital Twin

Key Trends	Timeline	Impact
Key Trend 1: Smart Cities is the term given to advances in powerful technology and the convergence of physical and digital realms to make more informed decisions about how to deliver and manage infrastructure assets.	**Next (5-10 years)**	**High**
Key Trend 2: National Digital Twin - The digital twin is more than just a model, as it enables positive interventions back into the physical twin. Using these digital twins means we can better support the design, operation and maintenance of many aspects of our world, making it safer and more efficient.	**Next (5-10 years)**	**Med**

10.2.1 Smart Cities

The fourth industrial revolution – the term given to advances in powerful technology and the convergence of physical and digital realms – is increasingly helping engineers to make more informed decisions about how to deliver and manage infrastructure assets. Key to this is the availability of accurate, real-time data about infrastructure condition and performance. But as technological capability increases, we have to be sure that this data is used in the best interests of end users, i.e. society. There is a range of definitions of a smart city, but the consensus is that smart cities utilise IoT sensors and technology to connect components across the city. This connects every layer of a city, from the air to the street to underground. It's when you can derive data from everything that is connected and utilize it to improve the lives of citizens and improve communication between citizens and the government that a city becomes a smart city. Smart city case studies will be examined further in ***Paper 3: Infrastructure***. We have a long way to go to perfect the ways that built environment data is accessed, used and shared, and to deliver full benefits to planning, performance, safety, and national security. But one solution could be through use of digital twins, and a current initiative to create a "national digital twin" of the UK's infrastructure system.

10.2.2 National Digital Twin

The National Digital Twin is not a huge singular model of the entire built environment. Rather, it is an ecosystem of Digital Twins that are joined together via the secure, resilient interoperability of data. A digital twin is a digital representation of something physical, such as a building, a bridge, or a stretch of motorway. Driven by real-time data from the physical asset, the digital twin can be used to understand how a bridge would respond to loading and usage changes, or how traffic flow patterns may impact motorway capacity. Crucially, the digital twin is more than just a model, as it enables positive interventions back into the physical twin. Using these digital twins means we can better support the design, operation and maintenance of many aspects of our world, making it safer and more efficient. The future vision is for digital twins is that they can be combined together to create a 'national digital twin', which enables better decision-making at system and national level. The national digital twin will not be a single digital twin of the whole built environment but an ecosystem of individual digital twins connected via securely shared data. The drive to make the national digital twin a reality is being led by the Digital Framework Task Group (DFTG), part of the Centre for Digital Built Britain (CDBB). They offer a useful Roadmap[28] for delivering the information management framework for the built environment. There are no specific timelines, it is a roadmap to help the Construction Industry get to a desired future state.

[28] Centre for Digital Built Britain (2018) Roadmap https://www.cdbb.cam.ac.uk/system/files/documents/DFTGRoadmap.pdf

Conclusion

Unless digitalisation, workflow integration and process optimisation is addressed, the future of Construction will remain uncertain. This report has introduced a four step approach that ensures that key questions are considered and that an organisation is ready to embark on a journey of digital transformation successfully. By examining ten identified themes through the lens of three Future Scenarios, key trends along with their potential impact were highlighted for further consideration, summarised in Table 2 below.

Theme 1: Connected workflows	Timeline	Impact
Key Trend 1: Big Data	Now (0-5 years)	High
Key Trend 2: Internet of Things (IoT)	Now (0-5 years)	High
Key Trend 3: Blockchain	Next (5-10 years)	High
Theme 2: Artificial Intelligence/Machine Learning	**Timeline**	**Impact**
Key Trend 1: Artificial Intelligence	Now (0-5 years)	High
Key Trend 2: Machine Learning	Now (0-5 years)	High
Key Trend 3: Generative Design	Now (0-5 years)	High
Theme 3: Wearable & Site Optimisation Technologies	**Timeline**	**Impact**
Key Trend 1: Inertial Measurement Units (IMU) sensor technology	Now (0-5 years)	High
Key Trend 2: Process monitoring and control	Now (0-5 years)	High
Key Trend 3: Wireless and wearable electroencephalography (EEG)	Next (5-10 years)	Med
Key Trend 4: Exosuits or Exoskeletons	Next (5-10 years)	High
Theme 4: Augmented Reality	**Timeline**	**Impact**
Key Trend 1: AR technology for tunnel segment displacement inspection	Now (0-5 years)	Low
Key Trend 2: Vision-based hazard avoidance system	Now (0-5 years)	Med
Key Trend 3: Augmented Worker System (AWE)	Next (5-10 years)	High
Key Trend 4: Drones	Now (0-5 years)	High
Theme 5: Industrialised Construction	**Timeline**	**Impact**
Key Trend 1: Future Opportunities for Industrialised construction (IC)	Now (0-5 years)	High
Key Trend 2: Factory-Made Housing	Now (0-5 years)	High
Key Trend 3: Platform Design for Manufacture and Assembly (P-DfMA)	Next (5-10 years)	High
Theme 6: 3D/4D Printing	**Timeline**	**Impact**
Key Trend 1: 3D Glass Printing	Next (5-10 years)	Med
Key Trend 2: 3D-printed bridges	Next (5-10 years)	Med
Key Trend 3: 3D-printed neighbourhood houses	Future (10-20 yrs)	High
Theme 7: Robotics	**Timeline**	**Impact**
Key Trend 1: Construction Robots	Next (5-10 years)	Med
Key Trend 2: Swarm Robotics	Future (10-20 yrs)	High
Key Trend 3: Intelligent Robots	Next (5-10 years)	Med
Theme 8: Construction Biotechnology & Advanced Materials	**Timeline**	**Impact**
Key Trend 1: Construction Biotechnology	Future (10-20 yrs)	Med
Key Trend 2: Graphene	Next (5-10 years)	High
Key Trend 3: Advancements in Concrete	Next (5-10 years)	High
Theme 9: Sustainable Design & Climate Change	**Timeline**	**Impact**
Key Trend 1: United Nations Sustainable Development Goals (UNSDG)	Now (0-5 years)	High
Key Trend 2: Committee on Climate Change	Now (0-5 years)	High
Key Trend 3: Net Zero Carbon Buildings	Now (0-5 years)	High
Theme 10: Smart Cities & National Digital Twin	**Timeline**	**Impact**
Key Trend 1: Smart Cities	Next (5-10 years)	High
Key Trend 2: National Digital Twin	Next (5-10 years)	Med

Table 2: Summary of Key Trends of Ten Identified Themes

In the first Scenario, *Building in a Virtual World,* the identified themes of Connected workflows, Artificial Intelligence (AI) & Machine Learning (ML), Wearable & Site Optimization Technologies, and Augmented Reality were examined. Although the technology associated with all these themes are available, their application have been limited. Improvements in connected workflows is the key to unlock their potential. This Scenario is very much here ***now*** (albeit at an embryonic stage in construction) and is the one that will develop the most in the next five year and continue to develop.

The second Scenario, *Factories Run the World*, examined the themes of Industrialised Construction, P-DfMA, 3D/4D Printing, Robotics and Construction Biotechnology & Advanced Materials. This scenario and associated themes are making rapid progress in many sectors, driven by Industry 4.0. In the Construction industry, however, only with meaningful progress made in the previous Scenario then perhaps we will see it flourish in the ***next*** (5-10 years) and ***future*** (10-20 years) time horizons.

The final Scenario, *A Green Reboot,* examined the themes of Sustainable Design & Climate Change and Smart Cities. This Scenario needs to be considered at all three time horizons given the pressing nature of the climate emergency and the key trends highlighted requires implementation today.

These Scenarios are not mutually independent and their evolution is very much driven by each other. The rapid developments in the virtual world can significantly enhance the value of factories that can integrate digitalised workflows and this will undoubted have a significant impact on enabling a green reboot through the generation of sustainable methods and materials.

By using the proposed Four Step approach as the foundation for effective digital transformation, combined with the Themes in Table 1 (Section 7) and their associated Key Trends (Table 2), a construction organisation could make an assessment of the potential opportunities that are most closely aligned to its current strategy or as a starting point for developing a more radical alternative.

The majority of this paper was brought together before the Covid-19 pandemic, which has brought to the fore a profound set of challenges to how we all do things currently. The fact that all key themes identified are still highly relevant despite recent setbacks gives some assurances that they will continue to be relevant. In McKinsey & Co's May 2020 report entitled *"How construction can emerge stronger after coronavirus"*, both its short and long term trends include *increased digitisation* and *further investments in technology or digitisation and innovation of building systems*. In addition, it proposes a set of actions for success which include: *accelerate rollout and adoption of digitisation* and *identify opportunities to shift work off-site*. It can be argued that an opportunity for new thinking and action has been imposed on us and the uptake of these themes will need to be expedited.

In order to assure a sustainable future, we must continue to look forward. This first themed paper provides an overview of the identified key themes in Construction. The approach used in this paper, along with the chosen research methodology will be applied to subsequent papers for Facilities Management and Infrastructure.

Erin Bradner [EB] Director of Robotics, Autodesk
Matt Keen [MK] Senior Industry Strategist, Autodesk Construction Solutions
Manu Venugopal [**MV]** Head of Construction Data & Analytics Products, Autodesk Construction Solutions

Our research partner, Autodesk, kindly agreed to interviews with their experts in different areas of their business. Autodesk is global multinational software corporation that makes software services for the architecture, engineering, construction, manufacturing, media, education, and entertainment industries. They employ over 10,000 people worldwide.

The following three questions were asked:

1. **What, in your view, are the key drivers as well as the main challenges for advancing digitalisation in the construction industry?**

2. **How do you see the future of construction in the next 5, 10 and 20 years? If possible, please provide your response in terms of**

   (a) the **most likely scenario** – *what might realistically be achieved* and
   (b) the **optimum scenario** – *what could potentially be achieved*?

3. **From the ten identified themes, how would you rank them in terms of their *impact on enabling digitalization* of the construction industry (1 = highest and 10 = lowest)?**

1. **What, in your view, are the key drivers as well as the main challenges for advancing digitalisation in the construction industry?**

"I think one of the main challenges is how we drive automation into the construction process – taking it from design through construction using connected workflows that prevent data loss and empower better decision making. We see that the business drivers for using automation are very clear - we lack enough skilled people, the cost of labour is increasing, and we have huge sustainability and climate change issues. Aging infrastructure, coupled with increasing globalisation and urbanisation, will challenge the industry to shift construction processes to facilitate change. Adopting design-to-make manufacturing processes (DfMA), alongside digital technology, can increase productivity and produce smarter assets, but it's only an enabler and needs to have an innovation mindset.

Autodesk talks a lot about working with our customers to help ideate, create, and implement an innovation and technology strategy that supports their project and business goals. We like to look at a more risk averse model that came from the Harvard Business review and breaks down how a construction company should think about their innovation and technology strategy.

First, you want to consider spending about 70% of time, energy, and resources that support the core processes you have in place today. What this means is looking at processes that making incremental changes that support your core operations. For example, it could be as simple as enabling a mobile device strategy to establish standards around safety.

Next, is to spend about 20% focusing on adjacent opportunities – expanding the existing business by adding products, capabilities or services. In construction this could mean a lot of different things, again because each firm is unique, but some examples might be scaling your BIM capabilities and turning them into consulting services; or even entering a new market segment.

Lastly is the 10%, which is really what we think about as horizon three, or those innovations you will investigate that are truly transformational – such as robotics or industrialised construction. We've seen companies try to take on too much, too fast, which does not lead to the outcomes they desire. The best results are seen when companies understand where they're at, and where they want to be, then use the 70/20/10 approach to make incremental changes that help to transform their projects and business.

We think about our strategy in the same way to help customers – breaking it down into three pillars of Digitise, Integrate, and Predict. The whole concept centers on integrating technology to enhance workflows and strategies that scale innovation today, while helping to plan for the future as new technologies emerge. As a software provider, Autodesk partners with industry to develop technology that aligns with and enhances critical workflows. And firms that are investing in the digital construction journey are starting to see the benefits. For example, BAM Ireland has seen significant improvements in terms of quality and safety performance from using data to be proactive rather than reactive. This is one area where we've seen significant opportunity from those companies that are willing to change their mindset and think differently about how they structure and condition data out. Companies like Van Wijnen, Skanska, and Balfour Beatty are also benefitting from digitization.

Other obstacles may hinder transformation, such as contractual structures and subcontractor supply chain. But as we move into new mindsets and standardise as an industry, we can challenge the status quo and drive change." - **Matt Keen, Senior Industry Strategist, Autodesk Construction Solutions**

"How do we lead the industry to improve outcomes: safety, quality, and timelines? The answer lies in collecting and understanding data. When you start looking at what's happening in the industry today – especially in the last five to eight years – we see the digitisation of different workflows. We help our customers digitise their workflows into a unified ecosystem that connects all phases of the project lifecycle that's also interoperable with other applications to enable data flow across different systems.

There is an enormous amount of data that's generated on the jobsite. Site supervisors or project engineers or project managers are overwhelmed with the volume of data available from mobile devices, drones, laser scans, 2D drawings, 3D models, and schedules. The problem with too much data is that there's no ability to harness that information unless you are using digital tools to break down data silos between project stakeholders and integrate workflows to improve project outcomes. If we only focus on a specific workflow or a task and store data separately, it's hard to make sense of the data, and you're not getting value from investing in technology to understand gaps and improve processes.

Now the question is how we help the industry move to a more assistive state, especially when you have all these large volumes of data available, or can you start analysing data automatically and start finding trouble areas more quickly." - **Manu Venugopal, Head of Construction Data & Analytics Products, Autodesk Construction Solutions**

2. **How do you see the future of construction in the next 5, 10 and 20 years? If possible, please provide your response in terms of**
(a) the **most likely scenario** – *what might realistically be achieved* and
(b) the **optimum scenario** – *what could potentially be achieved*?

"With Construction IQ and many of the partners Autodesk works with, we enable our customers to transform project data into actionable insight to anticipate problems and build with greater certainty to improve construction safety, quality, and timelines. The next level is applying Construction IQ across the Autodesk platform, so the machine learning algorithm provides recommendations and assists our customers with automating key workflows to fill in the gaps and eliminate redundancies.

As the industry advances, we will see how a digital twin concept will provide that golden thread across a physical project to offer more predictive analysis and recommendations for teams to make more informed decisions by accelerating and automating traditional design, production, and operational processes in a virtual environment. Our research team is also exploring Generative Design and applying machine learning algorithms to read drawings from an existing project and automatically generate 3D models to find optimal design options based on the project requirements and design constraints." - **Manu Venugopal, Head of Construction Data & Analytics Products, Autodesk Construction Solutions**

"Data is everything in today's world and will only become more of an asset to facilitate better decision-making. As firms put a stronger emphasis on using data to make less subjective and more robust decisions, the way we collect and synthesise data will change. With an industry that does not have overall objective benchmarks – apart from the EMR in construction – firms will start thinking about measuring performance differently to get a clearer picture of where they are and where they want to be.

The next step would be to apply that data to re-engineer the current ways of working to focus on more sustainable and methodical methods of construction like industrialised construction – DfMA and modular – on a mass scale. While firms are testing the waters, we haven't gathered enough data to build that business case. And if you're not surfacing the data as you do the process, you're not building a robust business case that people can make decisions on to drive adoption long term." - **Matt Keen, Senior Industry Strategist, Autodesk Construction Solutions**

"As you move beyond near term, and into medium term, people will start to really scale modular (prefab) building methods. I think what you're going to then start to see is other industries will start to come in and I think that the convergence of manufacturing and construction is going to be a huge thing and that's where I think you'll start to see things like robotics starting to take hold. An example of this is our recent collaboration with Boston Dynamics with an inspection robot called Spot.

You don't need a man walking around site doing inspections anymore, these guys will be able to do it and they'll be able to connect the data so that it could raise RFIs while they're actually going around the job site. So it could be doing that inspection and taking out some of that human element, where the risk comes from so I could see some of that happening. I think I'd say the things that we're looking at as an organisation are very much around what does the convergence of construction and manufacturing look like, how is it that we can build best in class products that reflect current workflows and then really push the boundaries in terms of future workflows.

I think the last thing is that robotics piece, it's near term for other industries like automotive and product manufacturing, it's not near term for construction. There are examples that show these large scale robots laying bricks but you start to think whether we want our industry to just lay bricks quicker. I think that's where you've got to say we need to be thinking about how we actually re-engineer the final product. I think that you're going to get people who will push the boundary and I'll be interested to see it but I think the horse will just go quicker in the near term". - **Erin Bradner, Director of Robotics, Autodesk**

3. **From the ten identified themes, how would you rank them in terms of their *impact on enabling digitalization* of the construction industry (1 = highest and 10 = lowest)?**

Connected workflow (1-highest impact)*, AI & ML (2), Robotics & Automation (3), Sustainable design and climate change (4=), Industrialised Construction (4=), Wearable and site optimization technologies (6), Augmented Reality (7), 3D/4D printing (8), Smart Cities & National Digital Twin (9),* ***Construction biotechnology and advanced materials (10-lowest impact).***

"The construction industry is undergoing a massive digitisation. And as you start to digitise, there is an enormous amount of data collected, so the question becomes, 'How do you harness data across workflows to enable better outcomes that impact your business?'

Connected workflows are integral as it can lead to better, faster, more cost-effective outcomes for contractors and owners. Breaking down data silos to capture, share, and manage construction data in real-time across the project lifecycle empowers contractors to think faster and anticipate future problems with greater certainty to reduce risk and increase quality to deliver better projects. With more insight into project data, contractors can use machine learning algorithms to identify patterns and modify behaviors to direct towards better outcomes related to safety, cost, and schedule.

Companies that implement data-driven construction approaches create better products, serve customers more effectively, and see increased ROI. However, data-driven construction only works if the data is correct and error-free. Therefore, automation is another theme that's gaining traction. Automation is a way to ensure accuracy by removing the risk of human error, streamlining processes to ensure quality and increase efficiencies.

An indicator of a company's success is its ability or inability to adopt technology. Regardless of where your company stands in the implementation of various technology solutions, the first step is to understand how your company could benefit from digitisation and connected workflows and create a custom plan that's unique to your organisation to gain value from trends, such as machine learning and automation that are driving the construction industry forward." - **Matt Keen, Senior Industry Strategist, Autodesk Construction Solutions**

Report Authors

Dr Michael Tong *Principal Investigator*

Department of Construction & Surveying, Glasgow Caledonian University

Dr Kenneth Lawani *Senior Lecturer*, Glasgow Caledonian University

Steering Group

James Gall Autodesk

Brenda Joyce Construction Scotland Innovation Centre

Mike King Robertson Group

Clare Reid Robertson Group

Margaret Watson Scottish Enterprise

Michael Wescourt Autodesk

Scott Wilson Robertson Group

Disclaimer

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